Estuary and Gulf of St. Lawrence Marine Ecosystem Overview and Assessment Report

R. Dufour and P. Ouellet (editors)

Science Branch
Department of Fisheries and Oceans
Maurice-Lamontagne Institut
850, route de la Mer
Mont-Joli (Québec)
G5H 3Z4

2007

Canadian Technical Report of Fisheries and Aquatic Sciences 2744E

Pêches et Océans Canada | Fisheries and Oceans Canada

Canada

Canadian Technical Report of Fisheries and Aquatic Sciences

Technical reports contain scientific and technical information that contributes to existing knowledge but which is not normally appropriate for primary literature. Technical reports are directed primarily toward a worldwide audience and have an international distribution. No restriction is placed on subject matter and the series reflects the broad interests and policies of Fisheries and Oceans Canada, namely, fisheries and aquatic sciences.

Technical reports may be cited as full publications. The correct citation appears above the abstract of each report. Each report is abstracted in the data base *Aquatic Sciences and Fisheries Abstracts*.

Technical reports are produced regionally but are numbered nationally. Requests for individual reports will be filled by the issuing establishment listed on the front cover and title page.

Numbers 1-456 in this series were issued as Technical Reports of the Fisheries Research Board of Canada. Numbers 457-714 were issued as Department of the Environment, Fisheries and Marine Service, Research and Development Directorate Technical Reports. Numbers 715-924 were issued as Department of Fisheries and Environment, Fisheries and Marine Service Technical Reports. The current series name was changed with report number 925.

Rapport technique canadien des sciences halieutiques et aquatiques

Les rapports techniques contiennent des renseignements scientifiques et techniques qui constituent une contribution aux connaissances actuelles, mais qui ne sont pas normalement appropriés pour la publication dans un journal scientifique. Les rapports techniques sont destinés essentiellement à un public international et ils sont distribués à cet échelon. Il n'y a aucune restriction quant au sujet; de fait, la série reflète la vaste gamme des intérêts et des politiques de Pêches et Océans Canada, c'est-à-dire les sciences halieutiques et aquatiques.

Les rapports techniques peuvent être cités comme des publications à part entière. Le titre exact figure au-dessus du résumé de chaque rapport. Les rapports techniques sont résumés dans la base de données *Résumés des sciences aquatiques et halieutiques*.

Les rapports techniques sont produits à l'échelon régional, mais numérotés à l'échelon national. Les demandes de rapports seront satisfaites par l'établissement auteur dont le nom figure sur la couverture et la page du titre.

Les numéros 1 à 456 de cette série ont été publiés à titre de Rapports techniques de l'Office des recherches sur les pêcheries du Canada. Les numéros 457 à 714 sont parus à titre de Rapports techniques de la Direction générale de la recherche et du développement, Service des pêches et de la mer, ministère de l'Environnement. Les numéros 715 à 924 ont été publiés à titre de Rapports techniques du Service des pêches et de la mer, ministère des Pêches et de l'Environnement. Le nom actuel de la série a été établi lors de la parution du numéro 925.

Canadian Technical Report
Fishery and Aquatic Sciences 2744E

2007

ESTUARY AND GULF OF ST. LAWRENCE MARINE ECOSYSTEM OVERVIEW AND ASSESSMENT REPORT

R. Dufour and P. Ouellet (editors)

Department of Fisheries and Oceans
Maurice–Lamontagne Institut
850, route de la Mer
Mont–Joli (Québec) G5H 3Z4

© Her Majesty the Queen in Right of Canada, 2007.
Cat. No. Fs 97–6/2744E ISSN 0706–6457

Correct citation for this publication:

Dufour, R., and Ouellet, P. 2007. Estuary and Gulf of St. Lawrence marine ecosystem overview and assessment report. Can. Tech. Rep. Fish. Aquat. Sci. 2744E: vii + 112 p.

Cette publication est également disponible en français.

TABLE OF CONTENTS

LIST OF FIGURES vii

LIST OF TABLES vii

ABSTRACT vii

RÉSUMÉ vii

1.0 INTRODUCTION 1

2.0 PHYSICAL AND CHEMICAL SYSTEM 2

2.1 Physical environment 2

2.1.1 Geomorphologic structure and characteristics 2

2.1.2 Descriptive physical oceanography 2

2.1.3 Dynamic physical oceanography in the Estuary and Gulf of St. Lawrence 5

2.1.4 Forcing 5

2.2 Chemical environment 9

2.2.1 Chemical characteristics of the water masses 9

2.2.2 Suspended particulate matter (SPM) 9

2.2.3 Nutrients 12

2.2.4 Oxygen 13

2.2.5 Organic carbon 14

2.2.6 Metabolism in the Gulf of St. Lawrence and carbon fluxes 17

3.0 BIOLOGICAL SYSTEM 18

3.1 Plankton community 18

3.1.1 Bacterioplankton 18

3.1.2 Phytoplankton 19

3.1.3 Zooplankton 19

3.1.4 Ichthyoplankton 21

3.2 Macrophytes 22

3.2.1 Macroalgae in the St. Lawrence system 22

3.2.2 The macrophyte distribution 22

3.2.3 Vascular plants in the St. Lawrence system 23

3.3 Zoobenthic community 26

3.3.1 Gulf of St. Lawrence benthic community 26

3.3.2 St. Lawrence Estuary benthic community 28

3.4 Fish Community **32**
3.4.1 Marine fishes 32
3.4.2 Diadromous fishes 34
3.5 Marine Mammals and Leatherback turtle **35**
3.5.1 Whales 35
3.5.2 Seals of the St. Lawrence 37
3.5.3 Leatherback turtles (*Dermochelys coriacea*) 37
3.6 Marine birds **38**
4.0 SOME ELEMENTS OF THE GULF ECOSYSTEM DYNAMICS **39**
4.1 Seasonal biological production cycles **39**
4.2 Lower Estuary–Gaspé Current–southwestern Gulf complex **40**
4.3 Northwestern Gulf (Anticosti Gyre) **42**
4.4 Northeastern Gulf **43**
4.5 Recent changes in the Gulf of St. Lawrence **44**
4.6 Marine food web dynamics **44**
5.0 HUMAN SYSTEMS **46**
5.1 Governance structures **46**
5.2 Human settlement and socio–economic profile **47**
5.3 Human activities **47**
6.0 HUMAN IMPACTS: STRESSORS RESULTING FROM HUMAN ACTIVITIES **49**
6.1 Disturbance **49**
6.1.1 Disturbance resulting from seismic and exploratory drilling activity related to the oil and gas industry 49
6.1.2 Disturbance resulting from marine traffic in the St. Lawrence and Saguenay Fjord 52
6.2 Impacts of the fishery activities **53**
6.2.1 Removal of biomass (unbalancing food web structure) 53
6.2.2 Habitat damage or destruction and ghost fishing by lost or damaged fishing gear ... 55
6.3 Invasive species **55**
6.3.1 Importance of invasive species in the Gulf of St. Lawrence 56
6.3.2 Potential introduction and range extension of invasive species 58
6.4 Climate change **60**
6.4.1 Potential effects of climate change 61
6.5 Freshwater inputs **62**

6.5.1 Impacts of freshwater runoff on estuarine, coastal and marine ecosystems.....63
6.5.2 Impacts on biodiversity 64
6.5.3 Links with fish stocks 65
6.5.4 Impacts of river development on flow variability 65
6.6 Chemical contamination 66
6.6.1 Sources, transport and distribution 67
6.6.2 Metals 68
6.6.4 Site of the *Irving Whale* 74
6.6.5 Polycyclic aromatic hydrocarbons (PAHs) 74
6.6.6 Organometallic compounds 76
6.6.7 New contaminants 79
6.7 Coastal eutrophication 80
6.7.1 Organic waste and nutrients associated with land–based activities 80
7.0 SPECIES OF CONCERN 82
7.1 Marine fish 82
7.2 Diadromous fish 83
7.3 Marine mammals 83
7.3.1 Beluga whale population status (Threatened) 83
7.3.2 Harbour porpoise population status (Special Concern) 84
7.3.3 Fin whale population status (Special Concern) 84
7.3.4 Blue whale population status (Endangered) 85
7.4 Seals 85
7.4.1 Harbour seal (Data Deficient) 85
7.5 Macrophytes 86
8.0 ACKNOWLEDGEMENTS 88
9.0 REFERENCES 89

LIST OF FIGURES

Figure 1. Map of the Gulf of St. Lawrence illustrating the Gulf of St. Lawrence integrated management project area and the most prominent bathymetric features. Isobaths of 100 and 200 m are shown inside the Gulf. 3

Figure 2. Typical depth profile of temperature, salinity and density observed during the summer in the Gulf of St. Lawrence. The cold intermediate layer (CIL) is defined as the part of the water column that is colder than 1°C. The dot–dashed line at left show a schematic winter temperature profile, with near–freezing temperatures in the top 70 m. 4

Figure 3. Map of the St. Lawrence Estuary. Lines indicate the approximate boundaries of the Upper (Île d'Orléans to the Saguenay River/Île aux Coudres) and Lower Estuary (Saguenay River to Pointe–des–Monts). Modified from the SIGHAP (Maurice–Lamontagne Institut, Mont–Joli, QC). 25

Figure 4. Cascading effect of the collapse of cod and other large predatory fishes on the Scotian Shelf during the late 1980s and early 1990s. The size of the circles represents the relative abundance of the corresponding trophic level. The arrows depict the inferred top–down effects. From Scheffer et al. (2005). 46

Figure 5. Pathways of impacts of freshwater influx on marine production 64

Figure 6. Concentrations of metals ($\mu g\ g^{-1}$) in surface sediments in the Lower Estuary (0 to 4 cm) and the Gulf of St. Lawrence (0 to 2 cm). From Gobeil (1991). 70

Figure 7. Total PAH in suspended particulate matter (SPM) and surface sediments (SED) observed at four stations and concentrations (ng Sn g^{-1}, dry sediment) of butyltins (TBT, DBT, MBT) in surface sediments of the Lower Estuary and Gulf of St. Lawrence. From Antonio Curtosi, UQAR, Rimouski, QC. 76

LIST OF TABLES

Table 1. List of the main stressors resulting from human activities in the Estuary and Gulf of St. Lawrence 87

ABSTRACT

Dufour, R., and Ouellet, P. 2007. Estuary and Gulf of St. Lawrence marine ecosystem overview and assessment report. Can. Tech. Rep. Fish. Aquat. Sci. 2744E: vii + 112 p.

The report's main objective is to provide a descriptive overview of the components, structure and functioning of the Estuary and Gulf of St. Lawrence ecosystem as well as a preliminary evaluation of the main pressures exerted by human activities at the ecosystem level. In doing so, the report identifies species/populations and geo–graphical areas, including marine coastal areas, that are either significant at the ecosystem level and/or of concern regarding the threat and impacts of human pressure on the Estuary and Gulf of St. Lawrence ecosystem.

RÉSUMÉ

Dufour, R., et Ouellet, P. 2007. Rapport d'aperçu et d'évaluation de l'écosystème marin de l'estuaire et du golfe du Saint-Laurent. Rapp. tech. can. sci. halieut. aquat. 2744F : vii + 123 p.

L'objectif principal de ce rapport est de décrire sommairement les composants, la structure et le fonctionnement de l'écosystème de l'estuaire et du golfe du Saint–Laurent ainsi que de fournir une évaluation préliminaire des principales pressions qu'exercent les activités humaines à l'échelle de l'écosystème. Pour ce faire, le rapport mentionne les espèces et les populations ainsi que les zones géographiques, y compris les zones côtières marines, qui sont importantes à l'échelle de l'écosystème et/ou préoccupantes en raison de la menace et des impacts que la pression humaine occasionne pour l'écosystème de l'estuaire et du golfe du Saint–Laurent.

1.0 INTRODUCTION

The Estuary and Gulf of St. Lawrence represent one of the largest and most productive estuarine/marine ecosystems in Canada and in the world. With a drainage basin that includes the Great Lakes, the St. Lawrence marine ecosystem receives more than half of the freshwater inputs from the Atlantic Coast of North America. The Estuary and Gulf of St. Lawrence (EGSL) ecosystem is also strongly influenced by ocean and climate variability in the North Atlantic, of both Arctic (Labrador Current) and tropical (Gulf Stream) origin. As a result, the EGSL exhibits large spatial and temporal variations in environmental conditions and oceanographic processes. This unique setting provides the conditions for a highly diverse and productive biological community and trophic structure.

The St. Lawrence marine ecosystem is exposed to a wide variety of human pressures and uses that pose significant threats to its integrity and sustainable use. In addition, The EGSL is intensively used for fisheries and navigation, particularly as a major transportation route to the interior of the continent. Furthermore, it is facing an ever–increasing demand from mariculture activities. Coastal development and recreational use (including marine mammal observation) also represent significant activities in the EGSL system. In addition, several land–based human activities are occurring at a high rate along the EGSL shores and in coastal and upstream rivers and tributaries, including industrial and municipal activities, agriculture, and river damming (for water level control and hydropower), all of which affect freshwater, nutrient, organic matter and contaminant inputs to the ecosystem. Ultimately, global processes such as climate change and long–range transport of contaminants also contribute to the human pressure on the EGSL ecosystem.

Because of this wide variety of human use and pressure, the Estuary and Gulf of St. Lawrence was one of the first marine ecosystems in Canada to be recognized as a Large Ocean Management Area (LOMA) that required action by the Government of Canada under the recently implemented *Oceans Act* to ensure the sustainable development of its human uses. In 2000, the Gulf of St. Lawrence Integrated Management (GOSLIM) project was thus initiated under the leadership of the Oceans sector of DFO (Figure 1). This initiative would provide the overarching management structure that would govern all Integrated Coastal Zone Management (ICZM) plans that are to be developed at regional and local scales within the ecosystem, including the establishment of Marine Protected Areas (MPA).

To support the development of a management plan for the Estuary and Gulf of St. Lawrence ecosystem, the Oceans sectors of the Québec, Gulf and Newfoundland and Labrador regions of DFO initiated the preparation of an ecosystem status report in 2001, with the collaboration of key internal and external scientists. A peer–review was conducted by the Science Sector of DFO in January 2005. The content and structure of the report were reviewed and information gaps were identified.

In February 2005, with the reading of its federal budget, the Government of Canada announced the implementation of the Oceans Action Plan (OAP). It also approved the pursuant funding of the first phase, which was spread over two years and included the preparation of Ecosystem Overview and Assessment Reports (EOAR) for five marine ecosystems in Canada, including the EGSL. In July 2005, a Coordinating Committee was formed with representatives from the Oceans and Science sectors of Québec, Gulf, and N&L regions as well as from the National Capital Region (NCR). This committee promotes close collaboration between all sectors and

regions involved in meeting requirements of OAP Phase I for the EGSL ecosystem. This collaboration was particularly critical for the GOSLIM initiative since the responsibility for the preparation and finalization of the EOAR under OAP Phase I had to be transferred from the Oceans sector to the Science sector.

As such, the present document is drawn mainly from the draft EOAR for the Estuary and Gulf of St. Lawrence ecosystem that was prepared by the Oceans sector in the three regions mentioned earlier, and also includes contributions from scientific experts in the three regions. These persons are: D. Alexander, T. Anderson, J. Brennan, G. Daborn, C. Devigne, J. Lawson, C. Mullins, J. O'Brien, L. Park and D. Sooley from the Newfoundland and Labrador Region; H. Benoit, G. Chaput, M. Chiasson, G.A. Chouinard, L. Currie, I. Frenette, T. Hurlbut, C. Leblanc, J. Legault, R. MacIsaac, R. Morin, C. Morry and D.P. Swain from the Gulf Region; M. Bourgeois, A.–M. Cabana, S. Mark, I. McQuinn, R. Methot, P. [illegible]is, M. Ringuette, A. Robillard and F. Saucier from the Québec Region; and S. Guittard, G. Poirier and D. Vecei from the National Capital Region.

2.0 PHYSICAL AND CHEMICAL SYSTEM

2.1 PHYSICAL ENVIRONMENT

2.1.1 Geomorphologic structure and characteristics

The Gulf of St. Lawrence (GSL) is a semi–enclosed sea, covering an area of about 240×10^3 km^2 and containing 3553 km^3 of water, that opens to the Atlantic Ocean through the Cabot Strait (104 km wide and 480 m in depth) and the Strait of Belle Isle (16 km wide and 60 m in depth) (Figure 1). The Lower St. Lawrence Estuary is generally included in the broad definition of the Gulf of St. Lawrence. The most prominent feature of the Gulf of St. Lawrence is a long and continuous trough, the Laurentian Channel that is over 300 m in depth and extends some 1250 km from the continental shelf to the Estuary. Two other deep channels branch off from the Laurentian Channel: the Esquiman Channel extends toward the Strait of Belle Isle and the Anticosti Channel extends into Jacques Cartier Strait north of Anticosti Island (Figure 1). By contrast, the southern portion of the Gulf is a wide and shallow plateau (average depth ca. 80 m). These geological features influence the circulation, mixing and characteristics of water masses. For example, the deep waters of the St. Lawrence enter from the Atlantic through the Laurentian Channel and are advected by estuarine circulation towards the channel head, at the Saguenay River mouth, where strong mixing occurs with near–surface waters.

In addition, the St. Lawrence River has the fourteenth largest drainage basin in the world, encompassing an area of 1 344 000 km^2 with a mean annual discharge of 10 900 m^{3}s^{-1} at Québec City (Bourgault and Koutitonsky 1999). The total freshwater runoff from the St. Lawrence River, the Saguenay River, rivers along the north shore, and smaller contributions from the south shore govern the mean (estuarine) circulation in the Gulf of St. Lawrence.

2.1.2 Descriptive physical oceanography

Over the deep (>~150 m) areas, the water column in the Gulf of St. Lawrence consists of three distinct layers: the surface layer, the cold intermediate layer (CIL) and the deeper water layer. In winter, the surface layer merge with the CIL and a two–layer vertical structure dominates (Figure 2).

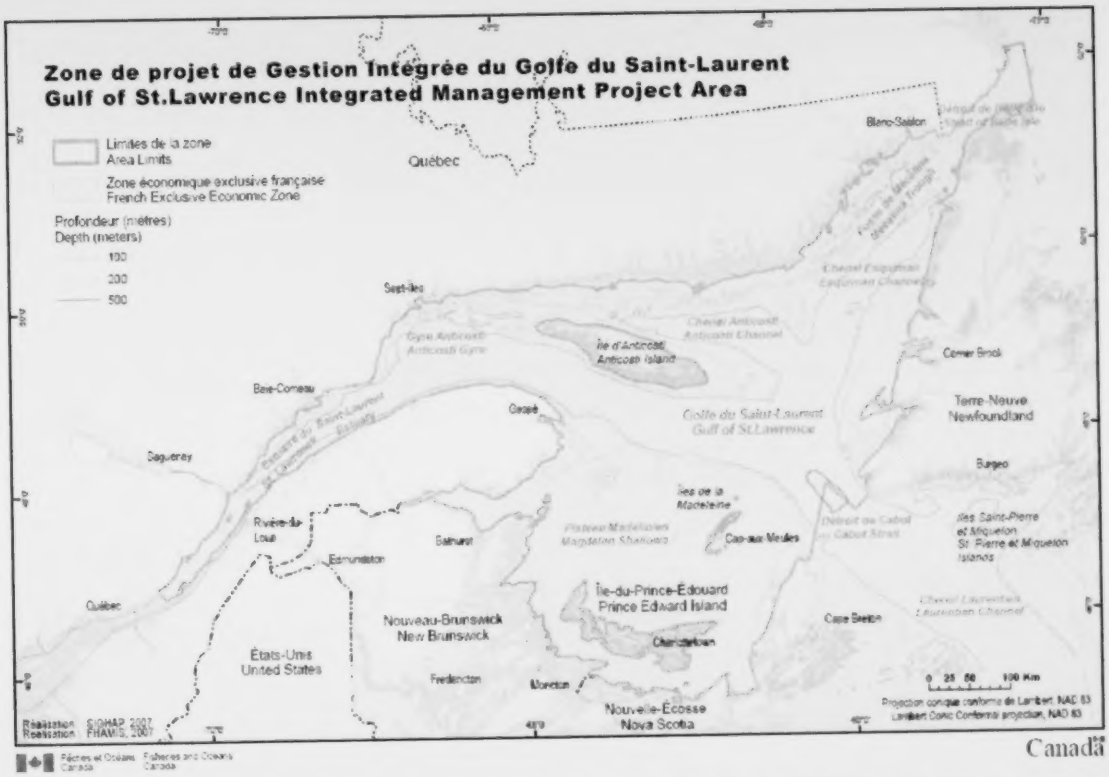

Figure 1. Map of the Gulf of St. Lawrence illustrating the Gulf of St. Lawrence integrated management project area and the most prominent bathymetric features. Isobaths of 100 and 200 m are shown inside the Gulf.

At the surface, vernal warming, sea–ice melt waters, and continental runoff produce a new low–salinity and higher–temperature surface layer each year. This layer flows toward the Atlantic Ocean and is partly mixed into deeper waters during fall and winter. During winter, the surface layer thickens partly because of buoyancy loss (cooling and reduced runoff) but mostly from wind–driven mixing and sea–ice formation during fall and winter (Galbraith 2006). The surface winter layer extends to an average depth of 75 m and up to 150 m in places at the end of March (intruding waters from the Labrador Shelf at the Strait of Belle Isle may extend to the bottom past 200 m in Mecatina Trough) and exhibit temperatures near freezing (–1.8 to 0°C) (Galbraith 2006). During spring, this cold water is trapped below the new summer surface layer and is partly isolated from the atmosphere. It then becomes known as the summer Cold Intermediate Layer (CIL). This layer will persist until the next winter, gradually warming up and deepening during summer (Gilbert and Pettigrew 1997) and more rapidly during the fall as vertical mixing intensifies.

The sources of winter waters are local formation and advection of Labrador Shelf waters through the Strait of Belle Isle (Lauzier and Bailey 1957, Banks 1966, Petrie et al. 1998). A lower boundary for the fraction of Labrador Shelf waters was found to be 3 to 30% (1996–2005), where the range is associated with inter–annual variability (Galbraith 2006). The intrusion of Labrador Shelf water affects on the productivity and species diversity in the Gulf of St. Lawrence by transporting nutrient–rich water and plankton species of Arctic origin (see sections

2.2.3 and 3.1).

The deeper layer below the CIL originates at the entrance of the Laurentian Channel and circulates towards the heads of the Laurentian, Anticosti and Esquiman channels. These waters have temperatures between 2 and 6°C and salinities between 32.5 and 35. Inter–decadal changes in the temperature of these waters are related to the varying proportion of Labrador Current water and slope water (McLellan 1957, Lauzier and Trites 1958). These waters travel from Cabot Strait to the Estuary in roughly two years or more.

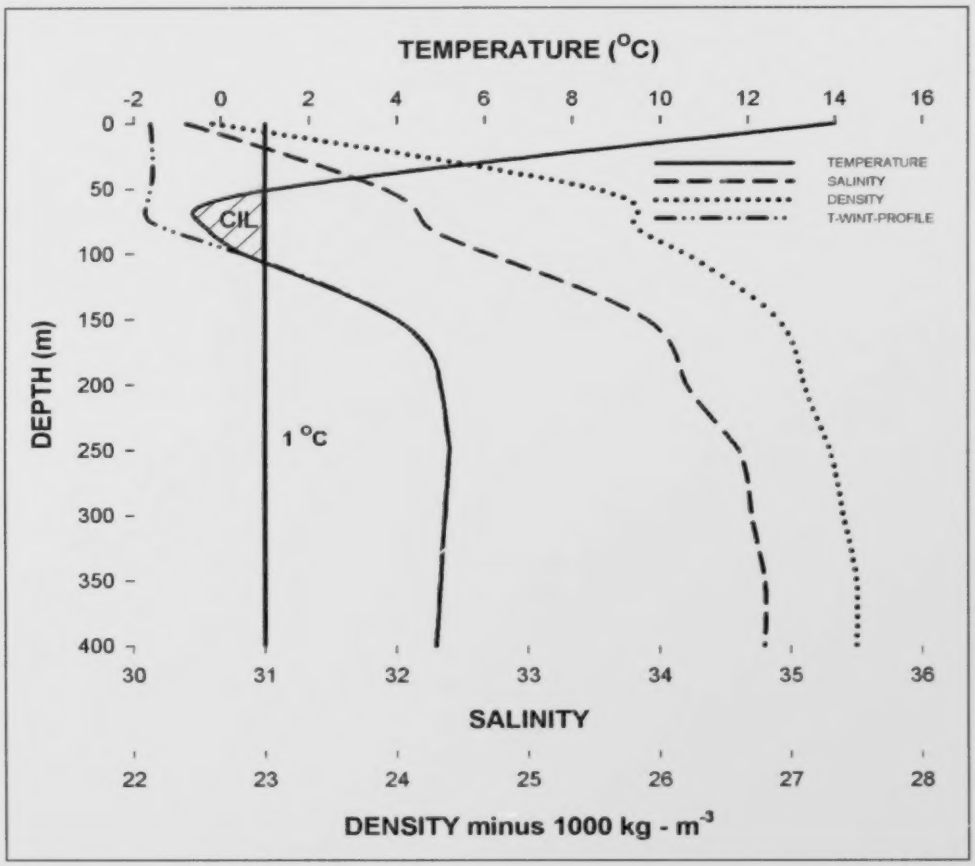

Figure 2. Typical depth profile of temperature, salinity and density observed during the summer in the Gulf of St. Lawrence. The cold intermediate layer (CIL) is defined as the part of the water column that is colder than 1°C. The dot–dashed line at left show a schematic winter temperature profile, with near–freezing temperatures in the top 70 m.

Sea ice

When sea ice is produced, salt is released back into the water column through brine rejection, which increases the salinity and thus the density of the surface layers. In the regions where this occurs (see below), free convection can lead to the mixing of the water column over 100 m in depth, contributing to the formation of the winter surface mixed layer of the Gulf of St. Lawrence. Winter convection is an important driver of primary production for the entire Gulf by

bringing nutrients (e.g., nitrates) to the surface that will support the phytoplankton bloom the next spring.

Sea ice is initially produced in December in the Estuary, the northwestern Gulf of St. Lawrence, along the north shore, and along the southeastern Gulf of St. Lawrence coast. Sea ice also forms early in the southern Gulf of St. Lawrence, where the shallow depths limit the heat content that can be stored in the water column during summer in spite of the warm water temperatures. Finally, sea ice is produced along the north shore, where wind–driven upwelling events efficiently remove the heat from the water column while pushing the ice away from the shore, sometimes promoting the creation of coastal leads. In February, sea ice production becomes important throughout the western and northeastern Gulf of St. Lawrence. Sea–ice formed in the western Gulf of St. Lawrence drifts southeast and accumulates in the southern Gulf of St. Lawrence. By mid–February the ice cover increases further in the southern Gulf of St. Lawrence and may begin to exit Cabot Strait. Sea ice may enter the Gulf of St. Lawrence through the Strait of Belle Isle from early on in the season, and many icebergs may drift inside the Gulf of St. Lawrence during spring. The head of the Laurentian Channel remains ice–free most of the winter (Galbraith et al. 2002, Saucier et al. 2003).

The year–to–year freeze–up and break–up dates, the maximum extent of the sea–ice cover, and the mean thickness vary greatly. Air temperature is the major predictor for the amount of sea ice that will be produced in the Gulf of St. Lawrence. Thus, much of the interannual variability may be attributed to the large–scale atmospheric circulation. In the context of global warming, climate models suggest that the Gulf of St. Lawrence will become ice free throughout the year in less than half a century. Observations made over the past decades do not support this prediction, with sea–ice conditions getting more severe in the Gulf of St. Lawrence (Parkingson 2000). Conditions since the mid 1990s have generally been mild, but it is yet too early to associate this change with global warming.

2.1.3 Dynamic physical oceanography in the Estuary and Gulf of St. Lawrence

2.1.4 Forcing

Forcing can be separated into atmospheric, oceanic sources, and runoff. Atmospheric forcing includes winds and atmospheric pressure, radiative transfer (e.g., solar heating) at the surface of the ocean, precipitation, and moisture and gas exchanges at the sea surface. Oceanic forcing includes the effects of variations in the ocean near the open boundaries of the Gulf of St. Lawrence, including sea level variations, currents, and the properties of sea water moving into the Gulf of St. Lawrence.

Atmospheric forcing

Atmospheric forcing, along with the ice conditions over the Gulf of St. Lawrence, defines the exchanges of heat, freshwater momentum, and gas at the air–sea boundary. Near–surface atmospheric variables play different and interacting roles in these cycles. Winds are important in moving the surface waters and for estimating the sensible heat transfer across the lower atmospheric layer. Cloud cover is the primary factor controlling the year–to–year variations in vernal warming. Air temperature directly controls sea–ice formation. Evaporation depends on humidity, sea–surface temperature, and winds. This evaporation along with precipitation (rain and snow) is related to significant seasonal changes in the surface salinity of the Gulf of St.

Lawrence.

Koutitonsky and Bugden (1991) discuss how the position of a storm track influences wind direction over the Gulf of St. Lawrence. The prevailing tracks in summer suggest that summer storms propagate in a southwest–to–northeast direction north and west of the Gulf of St. Lawrence (southwesterlies) or in a south–to–north direction east of the Gulf of St. Lawrence (southerlies). The prevailing directions in winter suggest that the winter storms pass in a southwest–to–northeast direction north and east of the Gulf of St. Lawrence (northwesterlies) or a higher north west–to–east direction (westerlies).

It has recently become possible to estimate the atmospheric circulation with relatively high accuracy over the Gulf of St. Lawrence using high–resolution atmospheric models (Maillot et al. 1997, Côté et al. 1997a, b). Pellerin et al. (2004) coupled a high–resolution (4 km) atmospheric model to an interactive ice–ocean model and demonstrated that the detailed ice–ocean conditions over the Gulf of St. Lawrence significantly modify the weather over the Gulf of St. Lawrence and the eastern Canadian seaboard. Faucher et al. (2004) and Gachon et al. (2002) also showed that the ice conditions in the Gulf of St. Lawrence modify wind strength, air temperature, and the cloud cover.

The atmosphere–ocean heat flux exhibits a strong seasonal cycle with large sensitive heat lost in the fall and winter and radiative heating in spring and summer. The monthly averaged differences in the heat flux among regions of the Gulf of St. Lawrence, controlled by the local stratification and sources of mixing, are generally as large as the seasonal variations (Saucier et al. 2003). Surface warming begins in April and usually reaches a maximum in August (Galbraith et al. 2002). Recent studies show that a 20% change in cloud cover during the April–July period could change the surface mixed–layer temperature by 1 to 2°C until fall (Saucier et al. 2003). The direction of heat flux changes in mid–September as the air becomes colder than the sea–surface temperature and incident radiation decreases. In late–fall and early–winter, a few strong wind events control the seasonal mean heat loss before the ice cover forms and therefore have a strong effect on sea ice growth in the months to follow. The monthly mean heat flux reaches a maximum in January, after which the ice cover and stratification at depth greatly reduce the heat flux.

Oceanic forcing

The Gulf of St. Lawrence is affected by changes in the Atlantic Ocean because the oceanic and shelf waters moving close to the bounding straits can enter the Gulf. The Tides and other waves produced in the ocean can also propagate into the Gulf of St. Lawrence through the open straits. These waves produce sea–level and current oscillations that provide an important and continuous source of mixing for the water masses therein.

The waters from the surface to 100–150 m that enter through the Strait of Belle Isle and the waters that enter through Cabot Strait are the same inner shelf waters that flow southward on the Newfoundland Shelf. Below 150 m in depth, the slope waters enter the Gulf of St. Lawrence through the mouth of the Laurentian Channel at the continental shelf break (Lauzier and Trites 1958, Bugden 1991). These waters are mixtures of Labrador Current waters, waters from the mid–Atlantic Bight, and waters from the Gulf Stream. The long–term changes in the properties of slope and shelf waters may explain a great fraction of the interannual and longer term changes in the Gulf of St. Lawrence's deep waters (Bugden 1991). One possible cause is the long–term

sea–surface height, which is affected by decadal–scale oscillations associated with the dynamic height of the slope waters (Petrie and Drinkwater 1993). Han et al. (2002) recently documented large–scale sub–decadal variations in sea level along the Newfoudland and Scotian shelves, which he related to the position of the Gulf Stream and the circulation in the Labrador Sea. It is not yet clear how these large–scale and long–term changes in sea level may affect the circulation into the Gulf of St. Lawrence.

Several components of astronomical tides are produced in the Atlantic Ocean and propagate into the Gulf of St. Lawrence through the open straits. The tides are of mixed character and dominated by the semi–diurnal lunar tide (Farquharson 1962, Godin 1979, Pingree and Griffiths 1980, Koutitonsky and Bugden 1991). The tidal currents are mostly barotropic, induce tidal rectification, and dissipate through the Gulf of St. Lawrence and the Estuary (Farquharson 1962, Saucier et al. 2003). They also produce strong currents in shallow regions of the Estuary and on the north shore. Tides are important in the Gulf of St. Lawrence because they produce turbulent energy through friction with the bottom as well as through internal gravity wave generation and dissipation.

Continental runoff

The runoff cycle is characterized by a strong spring freshet and a secondary peak in early fall. Historical records, available since the early 1920s, exhibit large inter–annual to inter–decadal variability. This variability includes the effects of flow regulation since the 1950s and of large–scale weather patterns over North America (Bourgault and Koutitonsky 1999).

The effect of the freshwater runoff rate on circulation is normally very important in estuaries, and that is certainly true for the Gulf of St. Lawrence. However, because of the complexity and variability of the processes affected by runoff, and the addition of other important factors controlling the general circulation (e.g., winds), it has not yet been possible to clearly relate changes in the circulation to changes in runoff. Even in the case of surface circulation, other than knowing that freshwater runoff initiates the surface summer layer and its circulation, little is known on how the surface circulation patterns, and even less the deeper circulation, are affected by changing runoff. Drinkwater and Gilbert (2004) have presented data that tentatively indicate a tendency towards lower surface salinities and weaker surface layer stratification in the northern Gulf of St. Lawrence.

Circulation

The mean surface geostrophic circulation during the ice–free months in the Estuary and Gulf of St. Lawrence was first described by Trites (1972) and El Sabh (1976). However, we know much less about the circulation below the surface layer in summer or during winter in general, or of the variations associated with the seasonal cycle or longer term changes in the forcing. The only consistent Gulf of St. Lawrence–wide results on circulation at depth come from Saucier et al. (2003).

Tides dominate in some regions and govern the instantaneous variations in the currents. This is true in the Upper St. Lawrence Estuary and other shallow regions of the Gulf of St. Lawrence. In these regions, it is possible to predict the tidal currents and produce charts (Canadian Hydrographic Service 1997, Saucier et al. 1999). The surface circulation also exhibits very strong features such as coastal currents, gyres, large eddies in the Estuary, and tidal fronts, which

have individually been the subjects of recent studies (Mertz and El Sabh 1989, Gratton et al. 1988, Mertz et al. 1991, Savenkoff et al. 1997, Gan et al. 1997, Marsden and Gratton 1998, Saucier and Chassé 2000).

Saucier et al. (2003) computed the mean seasonal surface currents in the Gulf of St. Lawrence. These results were in general agreement with those of El Sabh (1976) and with the general understanding of the surface circulation in the Gulf of St. Lawrence. The principal feature of the St. Lawrence River outflow is a strong coastal current along the length of the Gaspé Peninsula (the Gaspé Current) that flows seaward and disperses the St. Lawrence runoff in the northwestern and the southern Gulf. The waters in the southern Gulf, between the Îles–de–la–Madeleine, P.E.I. and the western side of Cape Breton, form the main outflow of the Gulf on the western side of Cabot Strait. On the eastern side of Cabot Strait, an inflow from the Atlantic flows north eastward along the west coast of Newfoundland. The cyclonic gyre west of Anticosti Island that characterizes the north western Gulf was also well simulated. The waters from the Strait of Belle Isle move westward along the northeastern shore. However, large differences were noted between simulated years. For instance, large differences were found in the mean circulation of the southern Gulf of St. Lawrence between summer 1998 and summer 1999. Such variations are due to the integrated effects of year–to–year differences in winds, runoff, and density changes, which govern the local climate, productivity, and habitat properties (e.g., ventilation, temperature).

A first estimate of the seasonal cycles in the circulation of the intermediate waters in the Gulf of St. Lawrence for the years 1998 and 1999 was also produced. The circulation is generally cyclonic and may be partly driven by inflows through the Strait of Belle Isle. In general, the waters inflowing at depth through the Strait of Belle Isle follow the lower north shore and propagate through Jacques Cartier Strait or move around Anticosti Island to reach the northwestern Gulf of St. Lawrence a few months later. They will reside for about one year in the Gulf of St. Lawrence and finally exit through western Cabot Strait. Complex circulation at the mouth of the Estuary was simulated, where key exchange processes occur for renewing its salt waters. The interannual variations in some regions are quite large. During fall, strong winds and surface buoyancy loss cause the deepening of the surface mixed layer to about 50 to 100 m depth. In the Estuary, however, the stratification remains high and prevents the in situ formation of cold water at intermediate depth (Ingram 1983, Saucier et al. 2003). During spring, in association with the new freshwater layer established by the spring freshet, the cold layer that was formed in the northern Gulf of St. Lawrence and in the Laurentian Channel becomes a subsurface water mass and is allowed to flow into the Estuary.

In the 200 to 300 m deep layer, Gilbert (2004) has shown that the cross–channel average speed at which temperature signals travel in the Laurentian Channel is about 1 cm s^{-1}. This implies a two–year travel time from Cabot Strait to the mouth of the Estuary. Preliminary results based on the simulation for 1997 and 1998 are in agreement with this result (F. Saucier, Institut Maurice-Lamontagne, Mont-Joli, QC, personnal communication), as they show that the circulation below 200 m entrains waters from Cabot Strait to the mouth of the Estuary in about two years. These results suggest a significant seasonal cycle with stronger currents in the fall.

Mixing processes

Water masses are modified through mixing driven by tides, internal waves, wind–driven circulation, density–driven circulation, and the loss of stability due to surface buoyancy loss.

Water masses with the same (isopycnal) or different (diapycnal) density may mix. Mixing is usually further separated into vertical mixing, between layers of generally different densities, and horizontal mixing. Vertical mixing is the most important process affecting water masses (and also an important factor for the control of biological productivity). Tides propagating over the sills at the head of the Laurentian Channel produce very strong mixing of the different water masses that meet there (Steven 1974, Forrester 1974, Ingram 1975, 1976, 1983, 1985, Therriault and Lacroix 1976, El–Sabh 1979, Gagnon and El Sabh 1980, Galbraith 1992, Bourgault et al. 2005). Tidal mixing is also a permanent and dominant modifier of the intermediate and deeper waters near the head of Jacques Cartier Strait and in the Strait of Belle Isle (Lu et al. 2002, Saucier et al. 2003). The wind–driven mixing together with the tides and the local stability of the surface waters will determine the deepening of the summer and winter surface layers (Saucier et al. 2003).

Storm surges, shelf waves and wind waves

Storm surges and shelf waves produce oscillations of sea level on the order of 10 to 50 cm, and sometimes over 1 m, that last for a few hours. When added to tidal oscillations, they may give rise to flood conditions over shorelines of the southern Gulf of St. Lawrence, the north shore, and the Estuary, including the upstream region near Québec City. These waves are produced by the inverse barometer effect and direct wind stress on the sea surface.

Surface waves are produced by the sea–surface wind stress. The surface waves may reach several metres during storms, and the complexity of the wind fields, the topography, and the interactions with the currents give rise to complex patterns. Surface waves and accompanying Langmuir cells[1] are the key drivers of mixing in the surface layer during the ice–free months.

2.2 CHEMICAL ENVIRONMENT

2.2.1 Chemical characteristics of the water masses

The different chemical properties of the surface waters exhibit a strong seasonal cycle controlled by sea–ice cover, freshwater runoff, stratification and circulation. To a large extent, physical mixing controls the distribution of most nutrients, organic matter, dissolved trace metals, suspended particular matter, and bottom sediments. This appears particularly true in the Estuary, where the water column remains stratified longer than elsewhere. Physical processes that occur on time scales ranging from few hours to a year and from few metres to kilometres also affect biological processes.

2.2.2 Suspended particulate matter (SPM)

The St. Lawrence River transports among the lowest amount of sediment per unit drainage area of any river in the world. This is due partly to the Great Lakes, which form large settling basins, but also because of the climatic conditions and the geology of the drainage basin. Nonetheless, the spatio–temporal distribution of suspended particles and their granulometric properties (composition and particle size) need to be studied given the implication of suspended particulate matter (SPM) in sedimentation and biogeochemical and biological processes. These processes

[1] Winds–generated surface currents that spiral around an axis parallel to the wind direction.

are particularly important in estuarine and coastal waters such as the Estuary and Gulf of St. Lawrence, where wind, waves, tides, and currents play important roles in particle dynamics.

SPM transport and distribution

Particulate matter is carried both vertically and horizontally by prevailing currents, gyres, and tidal action in the Estuary and Gulf of St. Lawrence. The Anticosti Gyre and estuarine flow tend to retain water and cause eventual settling of particulate matter onto the sediments. Extreme tidal forces in the Upper Estuary and upwelling due to topography at the heads of the Laurentian, Anticosti, and Esquiman channels tend to move particles vertically within the water column. The strong bottom currents in the Upper Estuary, the Gaspé Current, the general circulation patterns in the Gulf, and the water exchange through Cabot Strait are all forces that move particles over large distances.

The geographic and SPM bathymetric distributions are very heterogeneous over the scale of the Estuary and the Gulf. The general pattern of surface SPM concentrations is modified by biological processes such as phytoplankton blooms that cause localized maxima or by river outflow that favours particle resuspension. In the Upper Estuary, concentration range of 0.1–250 mg l^{-1} from May to September, with the maximum concentrations observed in surface layers (0–25 m), during the spring freshet, and in the maximum turbidity zone (Poulet et al. 1986). The lowest concentrations were observed in summer/autumn.

The maximum turbidity zone (MTZ)

The maximum turbidity zone–SPM concentrations from 50–200 mg l^{-1} with extreme at 400 mg l^{-1} of the St. Lawrence is located between Île d'Orléans and Île aux Coudres (shifting according to the tide and the flow of freshwater) in the Upper Estuary (d'Anglejan 1990). In this area, the large tidal range and strong tidal current mix fresh and salt waters and create highly turbid water. This zone has implications for the SPM characteristics downstream. For example, there are significant changes in element composition due to particle sorting during settlement and resuspension and to processes that alter sediment structure, texture, and mineralogy during deposition (diagenetic alteration) (Gobeil et al. 1981, d'Anglejan 1990).

Lower St. Lawrence Estuary

In the Lower Estuary, SPM concentrations decrease at all depths as one moves away from the head of the Estuary (Yeats et al. 1979, Poulet et al. 1986, Yeats 1988a). The intermediate and deep layers are relatively stable through time whereas the surface layer is more variable, as would be expected with variable freshwater discharge and biological activity. The Lower Estuary is considered as a major deposition zone. In fact, the estimated deposition appears to exceed estimated river sediment input, with the origin of the difference remaining unknown (d'Anglejan 1990).

Gulf of St. Lawrence

The SPM distribution in the surface layer of the Gulf of St. Lawrence is closely related to the surface circulation. Sundby (1974) found that the concentrations in this layer varied from 0.1 to 2.9 mg l^{-1}, with highest concentrations in the low salinity outflow from the St. Lawrence Estuary. The lowest concentrations are associated with the inflow of saline surface waters from

the North Atlantic. SPM concentrations are higher in the predominantly outflowing water on the south side of Cabot Strait than in the deeper (150–350 m), predominantly inflowing water of the central and northern part of the strait (Yeats 1988a). During fall 1998, Larouche (2000) also noted slightly higher concentrations of SPM at the head of the Laurentian Channel and lower concentrations towards the Gulf. Most of the water column in the Gulf, from depths of 0 to 50 m to 50 m off the bottom, contains low levels of SPM, with little variation between Cabot Strait and Pointe–des–Monts.

The particle–rich layer close to the bottom (< 0.4 mg l^{-1} of SPM, with an organic content generally less than 20%, Yeats 1988a), called the nepheloid layer, is well developed in the Laurentian Channel, where increasing turbidity caused by the friction of tides over the bottom (at the sediment–water interface) is observed towards the head of the channel and in the Esquiman Channel. In situ observations have shown that the characteristics (shape, size, concentration, and settling velocity of marine snow) vary at several time scales: near instantaneous, daily, and seasonally (Syvitski and Hutton 1996). Turbulence near the seafloor in the Gulf of St. Lawrence breaks up the flocs after their long descent through the water column and creates this layer made of smaller particles. The nepheloid layer provides food for benthic filter feeders; thus, their populations might be affected by the availability of SPM.

SPM composition

The chemical composition of SPM in the marine environment is controlled by a number of factors, such as the rate of primary production, the amount of terrigenous input (material eroded from the land), and the sinking rate. It is a complex mixture of organic and inorganic molecules.

In the Gulf of St. Lawrence, the inorganic components of the suspended matter are similar to the mineralogical composition of recent marine sediments. The organic content of SPM varies depending on the location and is usually lower in the Upper Estuary than in the Gulf. Based on carbon/nitrogen ratios (C/N), the sources of the organic matter appear to be more terrigenous (made from material eroded from the land surface) in the upper region and more from local marine production in the lower regions (d'Anglejan 1990).

SPM budget for the Gulf

The estimated SPM budget suggests that much of the river input is deposited in the St. Lawrence basin since the suspended matter leaving the Gulf is unlike the predominantly inorganic particulate matter carried by the rivers. The net export of SPM from the Gulf is an order of magnitude less than the amount carried by river transport, and the SPM at Cabot Strait is largely composed of organic matter produced in situ within the Gulf. Thus, virtually all the riverborne SPM settles inside the Gulf and mostly autochthonous material (material formed in place) is exported (Yeats 1988a). Calculations suggest that local particulate matter resuspension and deposition account for about 40% of the total Gulf sedimentation (Strain 1988).

The vertical transport of particulate matter is accomplished by fairly large, fast–settling particles (Silverberg et al. 1985). The composition of these settling particles is quite different from the underlying sediment, indicating that extensive degradation and transformation take place at the sediment surface and in the sediment (Gendron et al. 1986, Gobeil et al. 1987).

2.2.3 Nutrients

The three major nutrients found in sea water are nitrates, phosphates, and silicates. Nitrate is the most abundant of the nitrogen–containing compounds, but nitrite, ammonia, and organic compounds also contribute to biological productivity. Compared to nutrient levels in North Atlantic waters of similar depths, the bottom waters of the Gulf of St. Lawrence are considerably richer (Coote and Yeats 1979). This is due to the general circulation pattern in the Gulf and to the degradation and remineralization taking place in deeper waters (Yeats 1988b). Petrie and Yeats (2000) found that the Gulf was the primary source of nitrate on the Scotian Shelf during winter and a significant source of nitrate and silicate during spring and summer. Compared to northern and the eastern sections, the southern Gulf has relatively low nutrient concentrations (Brickman and Petrie 2003).

Nutrient distribution in time and space

During summer periods, the surface waters generally contain low levels of nitrate, phosphate, and silicate and the concentrations increase with depth from the surface to the bottom (Starr et al. 2002, 2003). Increases in nitrate and phosphate levels are attenuated in the bottom layer, whereas silicate levels increase with depth throughout the water column. The cold winter surface layer (winter mixed layer) shows higher concentrations than in summer, whereas the deep layer concentrations remain relatively constant.

While the northeastern region of the Gulf has concentrations similar to those found in Cabot Strait, the concentrations of the three key nutrients increase from Cabot Strait to the Lower St. Lawrence Estuary (Coote and Yeats 1979, Yeats 1988b, Brickman and Petrie 2003). The Magdalen Shallows has relatively low nutrient concentrations, although the subsurface waters may be slightly richer than waters at similar depths in adjacent areas (Coote and Yeats 1979).

Physical processes and productivity "hot spots"

The important mechanisms that bring nutrients to the surface layers, where they become accessible for the primary producers, occur at different time scales and differ in the various regions of the St. Lawrence. Winter convection brings nutrient to the surface layer. During spring, when surface waters warm up and stratification first sets in, phytoplankton cells are trapped in the well–lit layer and production is enhanced. Nutrients are then depleted and their renewal from below is inhibited by the pycnocline (sharp density gradient), so primary production will tend to decline. Hence, stratification can act in both a positive or negative way on primary production.

In the Estuary, the most important mechanisms are the intense tidal mixing between freshwater and saltwater and upwelling at the head of Laurentien Channel, also known as the nutrient pump (see Le Fouest et al. 2005). Relatively nutrient–rich water of the intermediate layer is also mixed into the surface layer by entrainment with the St. Lawrence River water and both form the Gaspé Current, which transports nutrients along the Magdalen Shallows toward Cabot Strait. These hydrographic processes are responsible for the high biological production as far as the southern Gulf. In the Gulf, nutrients are also supplied by wind–induced coastal upwellings (Québec north shore, southern Anticosti Island), buoyancy–driven gyres and eddies, and intrusion of Labrador waters through the Strait of Belle Isle.

An overall view of major areas and key processes for biological productivity in relation to

physical oceanography was investigated through modelling (Le Fouest et al. 2005): 1) the nutrient pump in at the head of Laurentian Channel, in the Lower St. Lawrence Estuary, with high nitrate concentrations; 2) the nitrate gradient in the centre of the Anticosti Gyre; 3) tidal mixing in the Jacques Cartier Strait and the coastal upwellings north of Anticosti Island. The coastal upwelling on the north shore were also visible, although less clearly. The front (horizontal gradient in water density) in the northwest Gulf region that is associated with the Gaspé Current can also be distinguished. This zone is known to be highly productive. Lastly, the downwelling region near the Newfoundland coast noted by Gilbert and Pettigrew (1993), characterized by lower nitrate concentrations in the surface waters (0–50 m), is also seen.

Recycling of nutrients

Even though primary production depletes nutrients in the surface layer, the reserve of deepwater nutrients is replenished by the decomposition of organic matter. Regeneration of nutrients within the intermediate and deep waters is also an important factor in explaining the nutrient distribution and concentrations in the Gulf (Yeats 1988b). Some of the plankton produced in the surface layer die and sink into the intermediate and deep layer, where the nutrients are regenerated through the process of bacterial remineralization. Nutrient levels therefore increase relatively quickly with depth and a portion of these regenerated nutrients is returned to the surface layers further upstream to be reused by the primary producers, thus forming an internal cycling of nutrients within the Gulf. This nutrient regeneration cycle also serves as an explanation for the increase in deepwater nutrient concentrations from Cabot Strait to the Estuary (Yeats 1988b).

Since nutrient regeneration requires oxygen, a corresponding decrease in oxygen concentration is seen in the deeper waters from Cabot Strait to the Estuary. If nitrogen is a limiting factor for primary production, an increased input of this nutrient could mean higher oxygen consumption in the lower layer, possibly leading to oxygen deficiency.

2.2.4 Oxygen

Oxygen is dissolved in seawater and is in near equilibrium with atmospheric oxygen in the surface mixed layer (~100% saturation). Biological and physical processes can affect the oxygen concentration, and physical barriers (stratification) can prevent gas exchange with the atmosphere and cause a departure from equilibrium. Generally speaking, the distribution of O_2 in the Gulf of St. Lawrence is the net result of:

– Gas exchange with the atmosphere in the surface layer;

– Biological O_2 production in surface waters due to photosynthesis;

– Biological use of O_2 (respiration) throughout the water column;

– Oxydation of organic material associated with bacterial degradation in intermediate and deep waters as well as in the sediment.

A typical vertical profile of dissolved oxygen shows a surface layer where oxygen is close to 100% saturation, an intermediate layer where oxygen saturation decreases steadily from spring to fall, and low oxygen saturation values in the deep waters. A general depletion of O_2 in the deep waters from Cabot Strait towards the head of the Laurentian Channel is also observed (Gilbert et al. 2005).

Geographic variation of oxygen in the bottom layer

The minimum oxygen values exhibit a marked decrease from Cabot Strait toward the western and northern ends of the Gulf, and the lowest concentrations have been found in the extremities of the deepwater troughs, i.e., in the Laurentian, Anticosti, and Esquiman channels. The saturation values decrease from 55–60% in Cabot Strait to about 20% in the Lower St. Lawrence Estuary and 25% at the heads of the Anticosti and Esquiman channels.

The reduction in oxygen content in the direction of the water flow indicates that local oxidative biogeochemical processes significantly affect the water entering the Laurentian Channel. The results of Yeats (1988b) indicated that the depletion was roughly linear, suggesting a uniformly distributed oxidation mechanism. Gilbert et al. (1997) noted that the oxygen concentration also diminished from the northeast to the southwest side of the Laurentian Channel because waters with higher oxygen concentrations usually enter the Gulf on the northeast side. Such differences in dissolved O_2 gradients can be used to estimate the corresponding CO_2 production flux (Savenkoff et al.. 1996).

Significance of hypoxia

A condition known as hypoxia occurs when the concentration of oxygen in water falls below the 2 mg l^{-1} level, minimal concentration that is necessary to sustain most animal life (Rabalais et al. 2000). The 2 mg l^{-1} limit is arbitrary and thus not necessarily appropriate everywhere, since metabolic rate and oxygen demand generally diminish with decreasing temperature (cold waters). Nevertheless, it has been shown that, at least for cod from the Gulf of St. Lawrence, such low O_2 values do have an impact (Plante et al. 1998).

Bottom oxygen concentrations have changed over the years. Gilbert et al. (2005) have shown that the dissolved oxygen content of bottom waters in the Lower St. Lawrence Estuary was twice as high in the 1930s than in the 1990s. This could imply that the areas affected by hypoxia are increasing. Between one half and two–thirds of the observed oxygen decline in the Lower St. Lawrence Estuary has been attributed to a 1.7°C warming of the bottom waters from the 1930s to the 1990s (Gilbert et al. 2005). To explain the remainder of the oxygen decrease, it has been hypothesized that the low oxygen concentrations are also partly caused by an increasing nitrogen load from land sources. Vertical profiles of percent organic carbon in sediment cores from the Estuary indicate that an increase in organic matter flux towards the bottom has taken place during the 20th century (Gilbert et al. 2005). This indicates that local oxygen consumption could explain part of the observed decrease in oxygen levels.

2.2.5 Organic carbon

Carbon plays a dominant role in the chemistry of life. It is the major chemical constituent of most organic matter: about 50% of the dry weight of living organisms is carbon. The transport of carbon dioxide to the ocean is often described as an important sink (reservoir) of anthropogenic carbon dioxide in the atmosphere. Vertical organic matter flux is believed to influence the global climate by leading to net burial of carbon in the seabed. Coastal zones are considered to be important to global carbon fluxes in terms of primary production, sedimentation, and sequestration of carbon.

One important hypothesis about the Gulf is that the fate of most of the organic matter exported from the euphotic zone is to be remineralized and returned to the surface layer (Tian et al. 2001).

In addition, the sediments in the Gulf of St. Lawrence are generally low in organic carbon compared to sediments beneath other areas of high productivity.

Organic matter components and sources

Traditionally, organic matter is divided into particulate and dissolved organic matter. Particulate organic matter (POM; including particulate organic carbon (POC) and nitrogen (PON)) is a mixture of living and dead phytoplankton and zooplankton, bacteria, and macroscopic organic aggregates often termed "marine snow". Vascular plants (tidal marshes), attached algae, and materials of terrestrial origin (water– or windborne) may contribute significantly to the coastal POM pool, but the main source remains phytoplankton.

Dissolved organic matter (DOM) is a complex mixture, not yet fully characterized, consisting largely of humic substances, carbohydrates, steroids, alcohols, amino acids, hydrocarbons, and fatty acids. Release of DOM has been demonstrated in growing algae (phytoplankton exudation) and upon decomposition or cell lysis of dead algae, POM degradation, sloppy feeding, and excretion by zooplankton and other organisms. Freshwater runoff is an additional source in estuarine and coastal regions. Regardless of its source, labile DOM is taken up by heterotrophic bacteria (those that derive their carbon from organic sources). These bacteria are then eaten by several types of organisms, eventually leading back to the classic food chain.

Produced largely in the surface layers, POC and DOC constitute the vertical carbon flux to the intermediate and deep layers of the ocean; this flux has been the focus of much current research. Until recently, POC was thought to play the major role in the Gulf, but newer findings suggest that DOC is more important than expected (Christensen et al. 1989, Lefèvre et al. 1996). DOC is the largest reservoir of organic carbon in the ocean, and thus a major intermediary in carbon transfers in the oceanic food webs and an important component in ocean carbon models (Packard et al. 2000, Tian et al. 2001).

Ocean carbon cycle

The ocean carbon cycle plays a key role in controlling atmospheric CO_2 levels. The net flux of CO_2 between the atmosphere and the ocean is controlled mainly by the balance among three processes:

– carbon fixation by phytoplankton;

– its remineralization back to CO_2 by respiration;

– the export of dissolved and particulate organic carbon toward the ocean depths and storage in sediments.

Carbon dioxide enters the ocean by dissolving in the surface waters where it is taken up by phytoplankton via photosynthesis and assimilated into organic matter. This process, known as carbon fixation, reduces the partial pressure of CO_2 in the surface waters and establishes a concentration gradient across the air–sea interface that, in turn, induces a flux of CO_2 from the atmosphere to the surface waters. Part of the organic carbon produced in the surface layer is exported from the euphotic zone in the form of aggregated phytoplankton, dead material and fecal pellets. This marine snow sinks toward the deeper waters where it can be converted back to CO_2 by bacteria—a process known as remineralization—or sequestered in the sediments and thereby removed from the upper ocean. The photosynthesis and the transfer of this organic

matter to deeper waters are referred to as the "biological pump".

The vertical flux of organic carbon regulates the chemistry of the deep ocean. It is thought that this flux and the carbon sequestration in sediments may affect the uptake of anthropogenic carbon. However, organic matter has been relatively little studied in the Gulf of St. Lawrence. A recent study (1993–1998) in the Gulf of St. Lawrence has somewhat improved the understanding of processes involving biogenic carbon (Canadian Joint Global Ocean Flux Study [JGOFS], Roy et al. 2000).

Particulate organic carbon (POC)

In the surface layer, concentrations of POC peak in the spring, decline in early summer, and increase again in late summer, though not to levels as high as the spring maximum. The concentrations decline in the fall and are lowest in winter, when they are similar to concentrations found in Atlantic waters.

In the intermediate layer, POC concentrations increase early in the year and are thereafter stable until a decrease in late summer. In the deep layer, there is little change in either concentration or composition over the year, apart from lower mean concentrations during winter (Pocklington 1988).

Information on the geographical distribution of POC (and PON) is very limited. In late summer 1997, surface distributions showed a general gradient of concentrations from higher values in the Estuary to lower values in the Gulf (Larouche 1998). However, the trend was reversed in fall 1998, with Gulf values higher than those in the Estuary, reflecting the trend observed in the chlorophyll concentration (Larouche 2000). This seems to indicate that algal biomass is a major contributor to the POC pool in the St. Lawrence during the late summer to fall period.

Dissolved organic carbon (DOC)

Very little is known of the geographical distribution of DOC. Surface DOC measurements undertaken by Larouche (1998, 2000) in late summer 1997 showed the highest DOC values on the Magdalen Shallows and lowest on both sides of Anticosti Island. However, in fall 1998, no significant spatial variation was noted over the stations included in the study.

Results from Packard et al. (2000) showed that the DOC concentrations in the Gulf of St. Lawrence were more comparable to the low DOC content in continental shelf and oceanic waters than to DOC in estuarine waters. An injection of DOC–poor Labrador Sea water into the deep waters of the Gulf between April and June could explain, through mixing, the seasonal decrease that was observed in the deepwater DOC concentrations in the Anticosti Gyre and Anticosti Channel stations. The DOC increase in the surface layer during the same period could be explained in part by the organic matter input from the St. Lawrence freshwater runoff: DOC was associated with low–salinity water, especially in June. DOC production in the water column would also contribute to this increase (Packard et al. 2000).

The gross annual seaward transport of total organic carbon (TOC) is 25% of the autochthonous production in the Gulf as calculated by Steven (1974). The nature of the imported organic matter is not the same as that exported: the mean C/N ratio of organic matter in inflowing water is significantly higher than that in the outflowing water. This implies a net loss of nitrogen (0.5×106 t N y^{-1}) from the Gulf in organic form (Pocklington 1988).

Sediments in the Gulf of St. Lawrence are generally low in organic carbon compared to sediments beneath other areas of high productivity. The fate of most of the organic matter within the Gulf is to be remineralized or transported outside the Gulf by currents (Pocklington 1988).

2.2.6 Metabolism in the Gulf of St. Lawrence and carbon fluxes

Recent studies have looked more closely at processes within the Gulf, notably the seasonal variation in the carbon cycling and production. A seasonal change in food web structure from spring to summer has been observed (Rivkin et al. 1996) as well as differences in the net metabolism between the winter–spring non–stratified period and the summer–fall stratified period (Savenkoff et al. 2000).

The winter–spring period is associated with an autotrophic pelagic food web: predominance of large phytoplankton cells (diatoms), large zooplankton. This period is generally characterized by a mean surface temperature near 0°C, weak vertical stratification, and high nutrient concentrations. In one study (Savenkoff et al. 2000), the large–celled phytoplankton (mostly diatoms) made up 68% of the total phytoplankton biomass during the period and accounted for 56% of the total primary production. During the winter–spring period, diatoms tend to be present in the more turbulent water that increases nutrient availability. Bacterial biomass and activity are relatively low and the zooplankton is mainly herbivorous. This pathway usually involves the export of large amounts of organic matter by rapid sedimentation of large phytoplankton during the spring blooms and/or by grazing of zooplankton on phytoplankton (Savenkoff et al. 2000, Vézina et al. 2000).

The stratified summer–fall period (May–October) is associated with a heterotrophic food web: dominance of small phytoplankton cells, large heterotrophic dinoflagellates and ciliates, smaller zooplankton, and dominance of omnivorous transfers towards the zooplankton (Savenkoff et al. 2000). This period is generally characterized by a mean surface temperature higher than 10°C, a well–stratified water column, and low nutrient concentrations. The small–celled phytoplankton dominates the primary production and community respiration. Flagellates are better suited to low turbulence and low nutrient waters because they can increase their nutrient uptake by swimming. Bacterial biomass and production are relatively high. The zooplankton includes mainly omnivorous species such as heterotrophic dinoflagellates and ciliates (protozoa). The carbon passes through the microbial network, which is composed of small phytoplankton (cell size <5 μm in diameter), bacteria, and protozoans, and then to the zooplankton. This pathway is efficient for recycling and keeping carbon in the surface waters. Moreover, it seems to dominate the annual scale in the Gulf of St. Lawrence (Savenkoff et al. 2000).

Carbon export to deep water

Vézina et al. (2000) confirmed that the total biogenic carbon export to the deep waters is enhanced when food webs are dominated by large–sized phytoplankton (diatoms; the winter–spring scenario). They found that the increase is not necessarily due to an increased sinking loss of diatoms. Most of the increased export may be linked to the rise in total production associated with the blooms of large cells: higher phytoplankton production and abundance increase herbivory by all consumers in the food web, which in turn stimulates the production of detritus of all sizes, from dissolved to large particles. Given favourable physical conditions for physical mixing, export then becomes dominated by fluxes of dissolved and suspended particles, since these are much more abundant than large particles. In contrast, during summer, the nutrient

supply is cut off due to summer stratification; the associated decrease in total primary production leads to a reduction in DOC production and less export. The results of Vezina et al. (2000) concur with other studies that emphasize the role of dissolved and suspended organic matter in removing carbon from the euphotic zone.

Model simulations conducted for Bonne Bay (Newfoundland) suggest that physical mixing processes and physico–chemical aggregation processes are at least locally as important as shifts in trophic pathways in explaining the relative constancy of export flux in mid– to high–latitude marine systems (Tian et al. 2001). Results indicate that upward nitrate fluxes and new production may be much more evenly distributed in time over the annual cycle than is generally thought, due to fluctuations in wind stress (Tian et al. 2001).

3.0 BIOLOGICAL SYSTEM

3.1 PLANKTON COMMUNITY

More than 2,500 species of invertebrates and phytoplankton inhabit the Gulf of St. Lawrence system (Brunel et al. 1998). Bérard–Therriault et al. (1999) list 499 species of (mostly autotrophic) plankton that have been recorded or might be expected in plankton collections. Shih et al. (1971) recorded 213 species of zooplankton, more than half of which (110) occur as meroplankton (the larval stages of benthic animals). The greatest biodiversity in the Gulf (>1500 species) is associated with the benthos, many species of which have planktonic larvae that appear for short periods near the surface. When present, they may dominate plankton collections numerically, but periodic sampling can often completely miss these short occurences. The numbers of species known from the Gulf continue to change, both as a result of improved taxonomy, and because of new introductions and/or appearance (e.g., the diatom *Neodenticula seminae*). As with many coastal waters, diversity at any single point in the Estuary or open Gulf is often relatively low. Few species tolerate the stressful physical conditions associated with extreme temperatures, ice, tidal currents or turbidity, although those that do are often extremely abundant. Nonetheless, the large area of the system and the diversity of habitats yield an ecosystem that is highly productive and biologically diverse.

Because plankton is moved by strong currents, many parts of the larger Gulf are influenced by production processes occurring in the St. Lawrence Estuary or other estuaries such as those entering the southern Gulf. Species that have their centres of growth in estuarine areas may be found in plankton collections from areas that would not sustain them for long. This estuarine drift may be of some significance to predators such as larval fish.

3.1.1 Bacterioplankton

Little research has been conducted on the bacterioplankton in the Estuary and Gulf, significantly limiting our understanding of the system's food webs. In highly turbid waters, such as at the area of maximum turbidity in the Upper Estuary, a heterotrophic microbial food web is based largely upon bacterial production. Painchaud and Therriault (1985, 1989, also Painchaud et al. 1987) concluded that a decline in bacterial abundance recorded along the Estuary was due to osmotic stress, sedimentation or grazing, or a combination of these three factors. Subsequent work indicated that grazing by zooplankton must be intense in the Upper Estuary to balance its high heterotrophic production (Painchaud et al. 1995, 1996). Organic carbon derived from upstream becomes readily associated with suspended particles in the Estuary, which provide a physical as

well as nutritional substrate for heterotrophic bacteria. Bacteria in suspension are grazed by ciliates and dinoflagellates in a "microbial loop". In addition, however, bacteria attached to suspended particles become available to larger filtering animals such as the dominant copepods and cladocerans of the Estuary.

3.1.2 Phytoplankton

The autotrophic phytoplankton community of the Gulf is a typical coastal marine association, largely dominated in biomass by diatoms and/or dinoflagellates (Bérard–Therriault et al. 1999). Because of limited sampling, and the effects of water movements, the patterns of distribution inferred from collections do not necessarily reflect the region of successful population growth of phytoplankton. Nonetheless, earlier studies concluded that there were considerable differences in phytoplankton assemblages, succession, and production in different parts of the Estuary and Gulf. Therriault et al. (1990) recognized four sub–regions within the Lower Estuary: 1) a zone along the southern shore dominated by outflow from the St. Lawrence River; 2) an "upwelling" region along the north shore; 3) a "plume" region dominated by outflows from the Manicouagan and Aux–Outardes Rivers; and 4) a more stable transition zone adjacent to the Gulf. Primary production in the four subregions of the Estuary can vary from a low of 30 g C m^{-2} y^{-1} in the outflow region, to 90 g C m^{-2} y^{-1} in the upwelling area, >130 g C m^{-2} y^{-1} in the plume, and 190 g C m^{-2} y^{-1} near the Gulf (Steven 1974, Therriault and Levasseur 1985, Therriault et al. 1990).

The seasonal pattern of phytoplankton growth in the entire Gulf can be summarized as follow: the spring bloom, occurring in late April or early May, is characterized by rapid growth of large diatoms (*Thalassiora*, *Chaetoceros*). With the depletion of nutrients, the abundance of many of the larger diatoms decline, and several important dinoflagellates (e.g., *Peridinium*, *Alexandrium*, *Ceratium*) become numerically dominant. Diversity remains high during the summer, although chlorophyll concentrations and productivity remain low. A fall bloom may occur from September to November, although chlorophyll concentrations do not rise much above the summer levels. Areas of relatively high production are found in the Lower Estuary, the northwestern Gulf (and particularly along the Gaspé Peninsula), at the southern and western end of Anticosti Island and along Québec's north shore, with lower values on the western shore of Newfoundland and the Magdalen Shallows (Le Fouest et al. 2005).

In the Lower Estuary, strong river flows in spring wash surface plankton downstream and tend to prevent seeding of surface waters by diatom spores deposited in deeper water during the previous growing season (Therriault and Levasseur 1985, Therriault et al. 1990). Combined with the high turbidity in the Estuary, this results in later spring blooms in the Estuary than in the Gulf, restricting phytoplankton growth to a two–month period in mid–summer. However, from 1994 to 2001 the spring bloom in the Lower Estuary occurred earlier compared to previous years (DFO 2000a, 2002, Starr et al. 2002) probably due to decreases in spring run–off from the St. Lawrence basin during this period.

3.1.3 Zooplankton

As for other regions at similar latitudes in the north Atlantic, copepods of various species usually constitute the major fraction of total zooplankton abundance in the Gulf of St. Lawrence (de Lafontaine et al. 1991). Larvaceans, cladocera, and euphausiids make up most of the remaining numbers, although meroplankton can be seasonally abundant at specific locations.

Although less abundant, amphipods, chaetognaths, pteropods, and jellyfish may occasionally contribute a large fraction of the zooplankton biomass (de Lafontaine et al. 1991).

In the turbid Upper Estuary, the principal species are small calanoids of the genera *Eurytemora* and *Acartia*, which constitute almost two–thirds of most samples. In addition, two species that are sometimes considered epibenthic, the harpacticoid copepod *Ectinosoma curticorne* and the mysid *Neomysis americana*, are commonly captured in near–surface tows, as a result either of vertical migration, or of upwelling processes. The holoplankton species show distinct zonation down the Estuary: *Eurytemora affinis* is most abundant where salinity is less than 5 (i.e., just upstream of the salt wedge), whereas *E. herdmani* and *A. longiremis* reach peak abundances in the higher salinities (20–28) of the Lower Estuary (Runge and Simard 1990). Of the non–copepod species, *Neomysis americana* is, because of its size, a major component of the biomass in the Upper Estuary. This species seems to do extremely well in turbid estuaries; it is omnivorous, able to sustain itself with plant and animal detritus when live prey is unavailable. Several small cnidarians (jellyfish), including *Sarsia tubulosa*, *Leuckartia octona*, *Rathkeia octopunctata*, and *Euphysa aurita*, have been recorded from other estuarine regions such as the Restigouche, Baie–des–Chaleurs and Miramichi, but rarely from the open Gulf.

There have been few systematic, large–scale surveys of zooplankton biomass, species composition and abundance in the Gulf of St. Lawrence before the implementation of the Atlantic Zone Monitoring Program (AZMP) in 1998, except in the Lower Estuary and the northwest Gulf of St. Lawrence, where a zooplankton biomass survey has been carried out since 1994 (Harvey et al. 2004) and in the southern Gulf area since 1982 (Castonguay et al. 1998). In the Lower Estuary, where cold Gulf water intrudes and salinities are > 25, the mesozooplankton species are dominated by typically marine copepods such as *Calanus finmarchicus*, *C. hyperboreus*, *Metridia longa*, *Microcalanus pusilis*, and *Oithona spp.* (Harvey et al. 2002). The zooplankton assemblage in this area also contains much larger forms that are also prominent in the Gulf, especially the euphausiids (krill) *Meganyctiphanes norvegica*, *Thysanoessa inermis*, and *T. raschii*. Because of their size, these animals often constitute a large fraction of the total biomass. They tend to migrate vertically, avoiding lighted surface waters during the daytime, rising to feed on other plankton during the night. Where they are abundant in the Gulf, they attract baleen whales.

Concerning the macrozooplankton, the dominant species found recently in the Lower Estuary and the northwestern Gulf of St. Lawrence was the mysid *Boreomysis arctica* (Descroix et al. 2005). Two euphausiid species (*Meganyctiphanes norvegica* and *Thysanoessa raschii*) were much more abundant in the Lower Estuary relative to the northwestern Gulf of St. Lawrence. On the other hand, chaetognaths, hyperiid amphipods, and siphonophores were relatively more abundant in the northwestern Gulf of St. Lawrence (Descroix et al. 2005). The inter–regional variations are attributed to different circulation patterns and different trophic systems. In addition, interannual variations in the abundance of the arctic and boreo–arctic species between the Lower Estuary and the northwestern Gulf of St. Lawrence may reflect variations in the inflow of Labrador Shelf waters entering the Gulf of St. Lawrence via the Strait of Belle Isle (Descroix et al. 2005)

Calanus finmarchicus, a key zooplankton species of the open Gulf, especially in deeper waters, is common in summer in some areas of the southern Gulf (Magdalen Shallows, St. Georges Bay) where the holoplankton is dominated by species typical of coastal and ocean regions. Outside Baie–des–Chaleurs, the copepod assemblage is dominated by *Calanus*, *Pseudocalanus*, and

Oithona (de Lafontaine et al. 1991). The Magdalen Shallows also appear to be a major nursery area for the euphausiids *Meganyctiphanes* and *Thysanoessa*, which mature in deeper, colder waters of the Gulf. Jellyfish, especially *Cyanea capillata* and *Aurelia aurita*, may be extremely important components of the summer plankton in the southern Gulf (Locke 2002). They occasionally occur in large, near–surface swarms that are not effectively sampled by regular plankton tows. Because they are major consumers of smaller plankton such as copepods and fish larvae, they can be important competitors for plankton–feeding fish such as herring.

AZMP data collected annually in late spring and fall along different sections into the whole Gulf of St. Lawrence showed that during the last five years (2000–2005) the average copepod abundance along the Bonne Bay section in the northeastern Gulf increases from late spring to late fall. The copepod assemblage is dominated by small copepod species, *Oithona sp.*, *Pseudocalanus sp.*, and *Temora longicomis*, which represented on average 50 and 65% of the total copepod abundance in late spring and between 60 and 85% in fall. On the other hand, the larger copepod species *Calanus finmarchicus* and *C. hyperboreus*, usually found in deeper water, are less abundant that the small copepod species but largely dominate in terms of biomass (> 80%). Concerning the macrozooplankton species, the two more abundant species are the hyperiid amphipod *Themisto abyssorum* and the chaetognath *Sagitta elegans* at all sampling seasons and years.

3.1.4 Ichthyoplankton

Because of the importance of the Gulf fisheries, there have been many studies of larval fish (and other meroplankton) over the years. These are summarized in de Lafontaine et al. (1991), Ouellet et al. 1994 and Locke (2002).

Because of the Gulf's latitude, the fish fauna is a mixture of both southern and northern species. Northern species, for which the Gulf is almost the southern limit, include capelin (*Mallotus villosus*) and northern wolffish (*Anarichas denticulatus*), whereas another group that includes mackerel (*Scomber scombrus*), fourbeard rockling (*Enchelyopus cimbrius*), and cunner (*Tautogolabrus adspersus*), is near its northern limit in the Gulf. Not surprisingly, these two groups have their centres of distribution in the northern Gulf and southern Gulf regions, respectively, although there is some seasonal overlap.

De Lafontaine et al. (1991) concluded that the ichthyoplankton of the Gulf represent different assemblages that are more or less spatially segregated, although as larvae grow and change both food and temperature preferences, these assemblages tend to become mixed. Ichthyoplankton abundance is generally higher in the Gaspé Current and the southern Gulf than in the more northerly regions (which may reflect the abundance of pelagic spawning species that are found especially in the southern Gulf), although the latter have been much less intensively sampled through time.

In the Estuary and western Gulf, de Lafontaine et al. (1984a, b) found that the relative densities and seasonal succession of more than ten species of fish occurring as eggs and larvae reflected unique combinations of the physical forces (i.e., the spring–neap cycle and advection) and the timing and location of spawning behaviour. At that time, they reported that cod (*Gadus morhua*), yellowtail flounder (*Limanda ferruginea*) and white hake (*Urophysis tenuis*) spawn near the mouth of the Estuary, whereas capelin (*Mallotus villosus*) and Atlantic herring (*Clupea harengus*) spawn in the Upper Estuary, and then drift downstream, entering the western Gulf primarily by way of the Gaspé Current. Bailey et al. (1977) found large concentrations of one–

year–old capelin between Pointe-des–Monts and Anticosti and relatively few on the southern shore.

Ouellet and Lefaivre (1994) analyzed the spring (May and June) ichthyoplankton and decapod crustacean larvae assemblage of the mid–1980s in the northern Gulf. Northern shrimp (*Pandalus borealis*) larvae dominated the large meroplankton species in early spring (May) followed by larvae of various crabs species (snow crabs [*Chionocetes opilio*]; *Hyas spp.).* Among the fish species, sand lance (*Ammodytes spp.*) and redfish (*Sebastes spp.*) larvae and cod or witch flounder (*Glyptocephalus cynoglossus*) eggs were dominant early in the season followed by the larvae of the Canadian plaice (*Hippoglossoides platessoides*), and various Stichaeidae and Cottidae species. The meroplankton species were especially abundant along the Québec's north shore, Jacques Cartier Strait, and over a shallow area east of Anticosti Island.

The southern Gulf appears to be a major nursery for several species, including Atlantic mackerel, sand lance, and Atlantic cod (Castonguay et al. 1998). The ichthyoplankton is dominated by sand lance and radiated shanny (*Ulvaria subbifurcata*) in the spring, and mackerel in summer. Occurrence, distribution and seasonality of the ichthyoplankton in the southern Gulf have been thoroughly reviewed by Locke (2002). She notes that circulation patterns within the southern Gulf are probably important in retaining larvae in the productive shallows west of Cape Breton. Such circulation patterns are influenced by tidal movements interacting with river flows: in areas such as Northumberland Strait, St. Georges Bay and the Strait of Canso, circulation may be modified both by human changes (e.g., construction of causeways and modification of river flows).

3.2 MACROPHYTES

Macrophytes are a component of benthic habitat architecture and are significant contributors to nearshore primary production. They contribute a small component (1 to 2%) of primary productivity in the context of open water bodies. However, in the nearshore environment and semi–enclosed bays or basins, as is the case for coastal areas in the St. Lawrence system[2], the portion of the total production and detrital pool of algae can be significant (Sharp et al. 2001).

Macrophytes are divided into two categories in this report: macroalgae (plants with no root system) and vascular plants (plants with a root system).

3.2.1 Macroalgae in the St. Lawrence system

Macroalgae are divided into three classes based on their color: Phaophyceae or brown algae, Chlorophyceae or green algae, and Rhodophyceae or red algae.

3.2.2 Macrophyte distribution

More than 346 taxa of algae have been documented in Eastern Canada (Cardinal 1990). Coastal zones in Eastern Canada are largely dominated by a number of groups of brown algae, particularly Fucaceae in the intertidal zone[3] and Laminariacae and Alariacae in the subtidal

[2] Include the Saguenay Fjord, the Estuary and the Gulf of St. Lawrence.
[3] The intertidal (or midlittoral) zone is the area that is affected by tides (Chabot and Rossignol 2003).

zone[4]. In the Estuary and Gulf of St. Lawrence, the relative number of brown algae diminishes gradually from north to south, while the number of green and red algae increases (Chabot and Rossignol 2003). With decreasing water salinity, the number of taxa decreases as well except for green algae, which are more tolerant to lower salinity.

In the lower intertidal zone in the northern part of the Gulf, the macroalgal cover is very dense. This zone is dominated by Fucacea on protected shores and by rock weed (*Fucus distichus edentatus*) on exposed shores. In the sublittoral zone, these algae are replaced by kelp beds (Laminariacea and Alariacea).

In the southern part of the Gulf, bladder wrack (*Fucus vesiculosus*), Irish moss (*Chondrus crispus*) and wire weed (*Furcellaria lumbricalis*) dominate the algal benthos in shallow waters up to 10 meters. Red algae like *Phyllophora ssp.* are prevalent between 10 and 20 m and the flora diminishes markedly after 20 to 25 m. Several notable intertidal algae of the Northwestern Atlantic shores are apparently absent (or only occur occasionally in localized populations) from this area; these include knotted wrack (*Ascophyllum nodosum*), rockweed and winged kelp (*Alaria esculenta*). The action of ice is almost certainly responsible for the near absence of these species.

Algal distribution in the St. Lawrence Estuary is typical of subarctic cold–water communities (Cardinal 1990). In general, the extent and presence of the species in the different zones are a function of the slope profile and the presence of environmental factors limiting urchin growth. Several alga species reach their upstream distribution limit in the Upper Estuary and most of them are not present above the polyhaline zone[5]. However, several species of Fucacea can reach the mesohaline zone[6].

Information about the algal flora of the Saguenay Fjord is extremely sparse due to limited algal research conducted in this region. Most of the Saguenay Fjord is characterized by steep rocky shores that are denuded of vegetation due to the strong action of ice. On more gentle slopes, few algal species are present. Higher temperatures and lower salinities might also explain the low alga diversity of the subtidal zone of this region.

3.2.3 Vascular plants in the St. Lawrence system

Marine vascular plants (or seagrasses) have a tremendous influence on their environment: they influence the shape and stability of the littoral zone by enhancing sedimentation and binding sediments against erosion; they multiply the microhabitats; they serve as a refuge for a large number of species; and they dictate biological interactions in shallow water habitats by serving as a source of fixed carbon for adjacent marine communities and food webs.

The prevailing habitats where vascular plants are found in the St. Lawrence system are saltwater marshes, salt marshes, salt meadows and eelgrass beds. Their locations are a function of the characteristics of the different hydrographic regions of the St. Lawrence.

---

[4] The subtidal (or infralittoral) zone is the area that extends from low tide down to depths where light is insufficient for algae development (Chabot and Rossignol 2003).

[5] Water with salinity between 18 to 30

[6] Pertaining to brackish water with salinity between 5 and 18

Saltwater marshes (Scirpus marshes)

Saltwater marshes prevail on fine substrate and their vegetation in this type of marsh is generally distributed according to the immersion time of tides. The saltwater marsh is also characterized by its lower sedimentation compared to salt marsh and by the presence of several salt pannes formed by the erosion of drifted ice.

Saltwater marshes are present only in the upstream portion of the Upper Estuary and in the Saguenay Fjord (Figure 3). Marshes are a key element in structuring the marine ecosystem. They act as filters by recycling water contaminants, either by direct absorption by vascular plants or by the micro–organisms that recycle organic matter. Additionally, they also enhance the water quality by the sedimentation, microbial activities and physico–chemical exchange.

The vegetation structure found in saltwater marshes offers excellent habitats and food resources for several species of invertebrates, amphibians, fish, birds, and mammals. Marshes are intensively used as reproduction areas and as feeding grounds for certain fish species.

Salt marshes (Spartina salt marshes)

Salt marshes are typical of maritime habitats composed of fine substrate. They are found in the mesohaline and polyhaline zones of the upper and middle portion of the midlittoral zone where the slope profile is gentle. As with the salt water marshes, the vegetation is distributed according to immersion time of tides. The greatest plant species diversity is observed in the salt meadow[7] where they form several plant aggregations (i.e., more than 35 species of plants).

In the Estuary, salt marshes are found in the area of St–Jean–Port–Joli (close to Saint–Roch–des–Aulnaies on Figure 3), where the vegetation gradually shows more maritime characteristics towards the Gulf (Figure 1). In the latter, the shore profile and substrate composition are not very suitable for the establishment of marshes. Salt marshes are found in small areas in river mouths, deep–water bays, lagoons, and sand spits. The marsh of l'Isle–Verte is the largest. Information about the distribution of the different wetlands of the Gulf is not extensive and several gaps exist. The marshes of the Îles–de–la–Madeleine cover a vast area; they account for more than a third of all the salt marshes of the Gulf.

The biological importance of salt marshes is very similar to salt–water marshes. They are significant habitats for several species of the marine fish (spawning, feeding, fry rearing and resting sites) and avian fauna (feeding, nesting and migration sites). Salt marshes are very important for fish; they offer protection from the strong currents and predators, and are also important feeding grounds. Some marshes, such as in the Kamouraska area (between Rivière–Ouelle and Rivière–du–Loup on Figure 3), are intensively used as a feeding area by many species of fish.

Several plants help to build and maintain marshes. The leaves of cord grass (*Spartina alterniflora*) pass oxygen to its smallest roots and aerate the substrate, thus helping to aerate oxygen–deficient marsh soils. This process enhances plant growth and enables small animals to live in the mud (Gibson 2003).

---

[7] Area only submerged by extreme equinox tides.

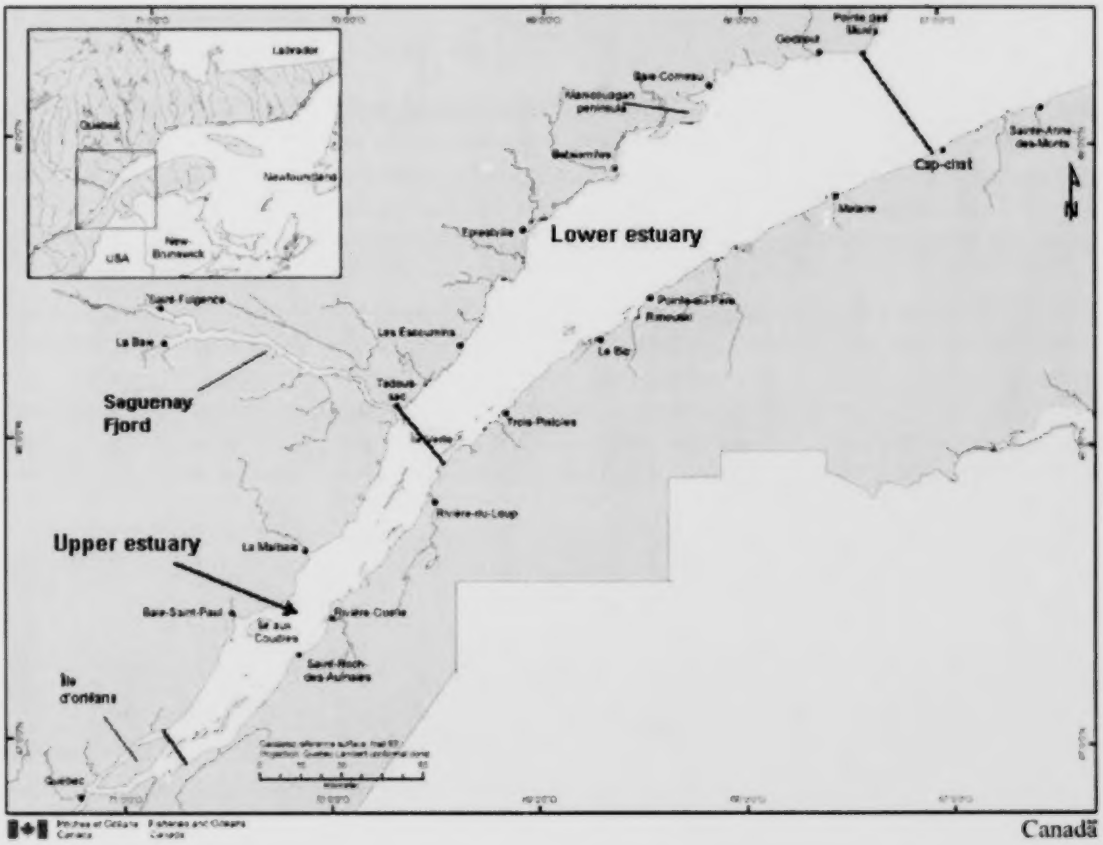

Figure 3. Map of the St. Lawrence Estuary. Lines indicate the approximate boundaries of the Upper (Île d'Orléans to the Saguenay River/Île aux Coudres) and Lower Estuary (Saguenay River to Pointe–des–Monts). Modified from the SIGHAP (Maurice–Lamontagne Institut, Mont–Joli, QC).

Salt meadows

Salt meadows are typical wetlands of the Gulf. They are found on coarse substrates such as sand and gravel. This type of wetland is generally not very diverse and can be divided into two levels of narrow vegetation bands: 1) the superior portion of the mesolittoral[9] zone, formed by a discontinuous cover of short halophyte plants; 2) the supralittoral[10] zone and dunal habitat.

Salt meadows are found principally in the Gulf of St. Lawrence, particularly on the north shore, Anticosti Island and Îles–de–la–Madeleine. The biological importance of this habitat is not well

[9] Equivalent to the midlittoral or intertidal zone: area affected by tides.
[10] The supralittoral zone is the upper part of the littoral not affected by the tides but may be touched by spray.

known but is probably an essential habitat for several animals.

Eelgrass beds

Eelgrass beds are composed of only one species of vascular plant, eelgrass (*Zostera marina*). Eelgrass beds are present in the midlittoral and infralitoral zones depending on the tidal amplitude. In areas exposed to strong tides, they will tend to be confined to the midlittoral zone.

Eelgrass beds are fragile and require specific environmental conditions in order to establish in an area. They are found in calm environments, on mud and fine or coarse sand. The highest density of eelgrass is found in sheltered areas such as tidal ponds (i.e., barachois), lagoons and sheltered bays with gentle slopes. Eelgrass beds are present in the Estuary and Gulf of St. Lawrence but are absent from the Saguenay Fjord.

In the Estuary, eelgrass beds are present up to Île–aux–Coudres and Rivière–Ouelle, but they are less abundant in the Upper Estuary (Figure 3). The largest eelgrass bed is found in Cascapedia Bay near Gaspé. Eelgrass beds outside Québec are widely distributed around PEI, northwestern Nova Scotia, and along most of eastern New Brunswick (except for the Baie–des–Chaleurs region).

Eelgrass beds are habitats known for their primary importance for the St. Lawrence ecosystem. They are recognized for their high primary productivity and are a key element in the coastal food chain. Eelgrass beds constitute important nurseries for a variety of species. The above–ground shoots provide food and shelter from predators for juvenile stages of many large fish (e.g., flounder, Atlantic tomcod, herring, and scullion) as well as smaller fish. Eelgrass beds also offer a surface where species can attach, a rare opportunity on sandy bottoms. They also provide a substrate for egg deposition for a number of species such as herring and supply habitat and food for a large number of animal species and epiphyte organisms. However, their precise role for fish is not well documented.

In addition, eelgrasses are known to alter the soil structure of their habitats. They reduce current speed and waves and increase sedimentation of suspended particulates. They also contribute to soil stabilization due to their rhizomes and roots. The combination of these two elements can help to lower the rate of the shoreline erosion.

3.3 ZOOBENTHIC COMMUNITY

The benthic community in any marine ecosystem is comprised of a wide variety of organisms ranging from bottom–dwelling groundfish and commercially valuable crustacea and bivalves to invertebrates and microorganisms of many forms with little or no commercial value but enormous ecological importance. The full list of species representing the diversity of the marine benthic community in the Gulf of St. Lawrence would likely number 3000 or more species.

3.3.1 Gulf of St. Lawrence benthic community

Macrobenthos

Crustaceans form one of the most visible and well–known groupings of benthic invertebrates in the Gulf, primarily because of their economic value. They can be loosely divided into: (1) large crustaceans, including American lobster (*Homarus americanus*), snow crab (*Chionoecetes opilio*), rock crab (*Cancer irroratus*), toad crab (*Hyas araneus* and *H. coarctatus*), (2) hermit

crab (*Pagurus sp.),* and (3) shrimp, including commercial species like northern shrimp (*Pandalus borealis*) and striped pink shrimp (*Pandalus montagui*) and noncommercial species like sand shrimp (*Crangon septemspinosa*).

Molluscs are probably the most diverse phylum of marine animals in the world (only the arthropods may be more numerous). Not all molluscs are strictly benthic (e.g., squid). For simplicity, most benthic molluscan fauna in the Gulf can be divided into bivalves and gastropods. Bivalves include both epibenthic[11] species like oysters (*Crassostrea virginica*), blue mussels (*Mytilus edulis*), giant scallop (*Placopecten magellanicus*) and Iceland scallop (*Chlamys islandicus*). The gastropods include such species as the common periwinkle (*Littorina littorea*), the commun whelk (*Buccinum undatum*) and many others. In addition to bivalves and gastropods, other forms of molluscs are also present in the benthos.

The echinoderms (e.g., green sea urchin–*Stongylocentrotus droebachiensis* and northern sea star–*Asterias rubens*) are not as homogeneous a group of organisms as is often thought. Twenty–one species of sea stars and four species of urchins leaves in the St. Lawrence estuary (Chabot and Rossignol 2003). They are aggressive predators on many benthic species, notably molluscs; in turn they form an important component of the food chain, being fed on by many bottom–dwelling fish species.

A tremendously varied group of organisms, the annelids (e.g., worms, leeches) can be considered true benthic organisms as many of them spend their entire life cycle on the bottom or in the sediment. Only a limited number of the polychaetes have economic value. Their true value is an ecological one, serving as one the principal groups of detritivorous animals, breaking down and recycling organic matter and also serving as a significant food item in the diet of many other marine species.

Sponges and cnidarians (e.g., corals, anemones) are considered together because of their similarities in life form, being attached organisms associated primarily with rocky substrates, sometimes in colonies and sometimes as individuals. They function as filter feeders and are therefore more prevalent in shallower waters where light conditions promote greater growth of plankton. The cnidarians also include other organisms such as the hydroids and medusas, though the latter two are more planktonic than benthic. They are not as numerous or as diverse as in the tropics but nevertheless form a unique and valued component to the ecosystem.

Though listed among the other benthic invertebrates, phylogenetically the tunicates and other ascidians are chordates (Phylum Chordata) and are more closely related to the finfish and other vertebrates than they are to true invertebrates. The group includes several unique forms, none of which are solely endemic to the Gulf and many of which have been introduced accidentally to the Gulf by human activity.

Platyhelminth, nemertean and aschelminth worms, bryozoans and brachiopods are among the several other small orders of animals composing the benthic community in whole or in part that do not fall within the major classes of organisms described above. None are harvested commercially and, though some of the parasitic worms are potentially problematic from the point of view of their effect on the processing of commercial fish species, few are of significant

[11] Organism living on the bottom

economic concern. Their importance is therefore more associated with the role they play ecologically than in economic terms.

Microfauna and meiofauna

The microfauna and meiofauna are mainly constituted by amphipods, isopods, opossum shrimps (mysids) and euphausiids as well as the closely related barnacles (e.g., *Semibalanus sp.*). All of these form an important component of the benthic environment as scavengers and detritivores. For the most part they are epibenthic, though some do burrow superficially in soft sediments.

Finally, unicellular, colonial algae, protozoa and bacteria are the smallest and most numerous organisms among the benthic flora and fauna. However, they are the ones that receive the least attention in the scientific literature. Algae, protozoa and bacteria form the main engine for primary and secondary productivity at the water/seabed interface. Below the surface they work aerobically and anaerobically to recycle the constant stream of detritus that descends from the water column above. In deeper water their ecological significance cannot be overemphasized. Benthic foraminifera are marine, unicellular eukaryotes that secrete a shell (test) of calcium carbonate or agglutinate mineral grains in an organic matrix. While they are among the most abundant organisms in deep–sea sediments and play a vital role in nutrient recycling, they serve another equally important purpose. Because they are more rugged and less susceptible to destruction by conventional sampling than other benthic microfauna, they serve as an excellent sentinel of environmental degradation. Their diversity and species composition changes as the environment becomes more eutrophic and anoxic and as inorganic contaminants accumulate in the sediments.

3.3.2 St. Lawrence Estuary benthic community

The St. Lawrence Estuary is one of the most important estuaries in North America (El–Sabh and Silverberg 1990). It stands out because of its significant size and the high variability of physical conditions. The variability in physical characteristics is reflected in benthic communities, which show a wide spectrum of compositions, densities, and biomasses. With these specific physical characteristics, benthic communities of the Estuary are often quite different from those observed in the Gulf of St. Lawrence.

Between 1975 and 1985, Bourget et al. (2003) sampled the benthic fauna found on 239 navigation buoys spread out from the fluvial St. Lawrence Estuary all the way to the Gulf. They provide a good overview of the larval distribution of epibenthic organisms and of the factors contributing to this distribution throughout the St. Lawrence River. Many studies done by E. Bourget and collaborators showed that 91% of the total number of species is found in the Gulf, while only 57% is found in the Estuary (Fradette and Bourget 1980, 1981, Ardisson et al. 1990, Ardisson and Bourget 1991, 1992, 1997, Bourget et al. 2003). As one moves from the Upper Estuary to the Lower Estuary and then onwards to the Gulf, abundance and biomass gradually increase and the number of species (sessile[12] and vagile[13]) increases dramatically between the different parts of the St. Lawrence River. These increases can be explained by hydrographic barriers (changes to physical conditions) that are significant enough between each

[12] Organism living permanently attached to a support
[13] Organism living on the bottom and moving freely

area of the St. Lawrence River.

The most significant physical factors affecting the occurrence of benthic organisms in estuaries and in the estuarine transition area of the St. Lawrence River are salinity and sediment characteristics (P. Nellis, Maurice–Lamontagne Institut, Mont-Joli, QC, personnal communication). These factors are largely controlled by hydrodynamic conditions. Furthermore, because of strong currents, certain types of sediment have drifted into the region, and because of dredging and filling operations, benthic communities in this region are also affected by sediment instability.

Usually, an increase in freshwater species can be noted upstream in an estuary. In the St. Lawrence Estuary, this increase is not significant (Fradette and Bourget 1980). Few studies have been conducted on the benthic fauna found in the sector between Île–aux–Coudres and the mouth of the Saguenay River (Figure 3). However, most authors included this sector with the Lower Estuary due to similarities in physical characteristics, such as salinity.

In the Lower Estuary, as in the Gulf of St. Lawrence, the nature of the substrate, tidal movements and water depth play a determining role in the littoral fauna composition. As salinity is relatively homogeneous in the Lower Estuary, this physical factor has only little impact on the general pattern of benthic communities. The influence of salinity can nevertheless be observed locally, especially in the mouths of rivers where the freshwater inflow is significant (Kimmerer 2002).

As water depth and tidal movement play a major role in the distribution of benthic organisms, oceanographers divide the littoral into various parts with distinct physical characteristics. The first layer (intertidal area) corresponds to the higher and lower limits of extreme spring tides. The second layer (infralittoral area) stretches from the low water limit to the lower limit of macrophyte algae growth. Finally, the last layer (circalittoral area) extends from the end of the infralittoral area to the edge of the continental shelf.

Intertidal area

According to the nature of substrate (rocky or soft), two communities (épibenthic and/or endobenthic) are generaly met.

Intertidal epibenthic communities living on rock substrates

The abundance and distribution of benthic fauna on rock substrates show horizontal (estuarine gradients) and vertical (tide level) gradients in the St. Lawrence Estuary. Based on blue mussel abundance, a species condidered as representative of the benthic fauna, low biomass levels are found in the upstream portion of the Lower Estuary, whereas high biomass levels are observed in the downstream region of the Lower Estuary.

Regarding vertical gradients, the intertidal zone can be divided into two layers. The upper portion is dominated in numbers by gastropods, but the densities remain low. In the lower part, an increase in total density is noted, mainly due to the increased abundance of blue mussels, barnacles, sessile polychaetes or anemones (Bourget 1997).

On a local basis, the factors controlling the structure of the intertidal community living on the estuary rock substrates will depend on the exposure of these substrates. On an exposed substrate, the community is controlled by physical factors, in particular by the substrate heterogeneity–ice abrasion tandem, and by larval behaviour. However, on a more sheltered substrate, or at least

when the community is not highly disturbed, biotic factors such as predation or competition are more likely to control the community.

Alga and benthic animal diversity is low on rock substrates in the St. Lawrence Estuary (Vincent 1990). The most prevalent species in these environments are blue mussels (*Mytilus edulis*), barnacles (*Semibalanus balanoides*) and winkles (*Littorina obtusata*, *Littorina saxatilis*). These species are often associated with two species of algae: bladder wrack (*Fucus vesiculosus*) and knotted wrack (*Ascophyllum nodosum*). Few species of commercial interest are found in this type community. Blue mussels are present here and *A. nodosum* is harvested at a small scale. However, no large–scale harvesting is made on wild populations in the St. Lawrence marine ecosystem: commercial landings result entirely from aquaculture farms.

Endobenthic communities living on soft substrates

Studies on the endobenthic community of soft (muddy and sandy) substrates have mostly taken place on the southern shore of the Lower Estuary. A community commonly seen on the soft–bottomed substrates is the boreo–Atlantic *Mya–Macoma* community. It is dominated by the filter feeders *Mya arenaria* and *Macoma baltica*. The polychaetes *Nereis virens* and *Nephtys caeca* as well as the gastropods *Hydrobia sp.* and *Littorina sp.* are sub–dominant species (Mark et al. 2003). A community dominated by the bivalve *Mesodesma arctatum* is also present in the fine sands of the north shore of the Lower Estuary. Currently, the softshell clam (*Mya arenaria*) is the only species harvested intensively.

Several biological or physical factors can influence the softshell clam distribution pattern. The physical factors are hydrodynamics, site exposure and sediment category. Biological factors are juvenile mortality, the presence of algal mats or predation (Hunt 2004). The main predators of softshell clams are nemertina (*Cerebratus lacteus*), gastropods (*Lunatia heros*, *Buccinum undatum*), crabs and birds. Certain fish, such as winter flounder (*Pseudopleuronectes americanus*), are also predators of softshell clams.

Infralittoral and deeper areas

Very few studies have been conducted on communities found in the infralittoral area of the Estuary and Gulf of St. Lawrence, and they concern rock substrate communities (Bourget et al. 1994). The gradient related to the estuarine position has a limited effect on the density of this type of community, with the density tending to decrease from downstream to upstream. On the other hand, local physical factors related to the depth gradient (change in temperature, salinity, exposure to waves, light intensity and barometric pressure) have a considerable negative effect on the density of the communities, but not on biomass and diversity. These two indices (biomass and diversity) probably have more to do with biotic factors, such as predation and competition.

These communities are dominated in biomass by the green sea urchin (*Strongylocentrotus droebachiensis*), sea star (*Leptasterias polaris*), brittle star (*Ophiopholis aculeata*) and sea squirt (*Ascidia sp.*). The green sea urchin, an effective grazer, can control the abundance of algae in the Lower Estuary. It appears that it does not exercise the same control in the Upper Estuary because it does not tolerate low salinity.

Several species of commercial value are present in the infralittoral zone of the Lower Estuary and Gulf of St. Lawrence. Although scarcely present in the St. Lawrence Estuary, one of the landed species with the highest commercial value in the Gulf is lobster (*Homarus americanus*).

This species is found in a broad spectrum of habitats but seems to prefer rocky bottoms less than 50 m deep covered with algae. The lobster distribution and recruitment patterns are influenced by a large variety of factors, spatial as well as temporal, during the phases of dispersion and recruitment. Lobster is a predator on green sea urchins and thus plays a role in regulating the urchin populations. The lobster's diet is composed of shellfish, mainly rock crab (*Cancer irroratus*), echinodermata, polychaetes and molluscs, especially mussels (*Mytilus edulis*, *Modiolus modiolus*). Most of the lobster's natural mortality stems from predation at various larval stages and predation from several types of fish (Hanson and Lanteigne 2000, Nelson et al. 2003) and birds (Ennis 1995). The other commercial species usually found in this layer in the Estuary include rock crab, green sea urchin (*Strongylocentrotus droebachiensis*), sea cucumber (*Cucumaria frondosa*) and commun whelk (*Buccinum undatum*).

As with the infralittoral area, very few studies have been conducted for deeper areas in the Estuary and Gulf of St. Lawrence. In general, abundance and diversity decrease from the head of the Laurentian Channel to the Gulf (Massad and Brunel 1979). Also, there are changes along the same gradient (upstream to downstream) of the trophic guilds. The community at the head of the Laurentian Channel is made up of several different guilds. In the downstream direction, these organisms are replaced by suprabenthic detritivorous species preferring vertical displacements. These species are gradually replaced by more mobile carnivorous and detritivorous organisms with horizontal displacements. Polychaetes (65%), bivalves (16%), amphipodes (8%), sipunculides (4%), and ophiuroides (3.5%) form the dominant taxa. Moreover, the shallow communities (< 75 m) are always more diverse than the communities living at greater depths.

Only one known study on the trophic structure of the macrobenthos (Desrosiers et al. 2000) was conducted on communities found in the deeper water layer. It concluded that the characteristics of the geomorphology (bathymetry, topography, and substrate) have an influence on the trophic structure and composition of benthic assemblages. The proportion of limnivorous surface or subsurface organisms, i.e., the nature of bioturbation activity, is related to the magnitude and pattern of the organic matter input from euphotic areas. The equal or the upper concentration of organisms in the subsurface zone, which manifest bioturbation strong activities of in sediment, was linked up with an irregular provision of organic matter.

Other commercial species of great importance are found in the deeper layers of the Estuary and Gulf of St. Lawrence. One of the most significant species is snow crab (*Chionoecetes opilio*). This crab is generally found on muddy and sometimes sandy bottoms at depths ranging between 45 m and 380 m (Bailey and Elner 1989). Several factors seem to affect snow crab distribution. The temperature and type of substrate appear to be the most important factors (Lefebvre and Brêthes 1991, Robichaud et al. 1989, Dionne et al. 2003). The diet of this species includes polychaetes of the genus *Sabellides*, crustaceans (shrimps, crabs and other small crustaceans), bivalves (*Macoma calcarea*) and fish (mostly capelin, *Mallotus villosus*) (Brêthes et al. 1982, Squires and Dawe 2003). One of the main causes of snow crab natural mortality is predation on young crabs (less than three years) by cod (*Gadus morhua*) and other groundfish species. The decrease in cod predation due to the collapse of stocks could partly explain the increase in the population recorded in the beginning of the 1990s. Moreover, cannibalism, especially between crabs of various generations (inter–cohort), would be one of the regulating factors for snow crab populations (Sainte–Marie and Lafrance 2002).

Another commercial species of interest found in these deeper layers is northern shrimp, (*Pandalus borealis*). The northern shrimp is usually associated with soft, muddy substrates and is

present throughout the Estuary and the northern Gulf at depths where the temperature is higher than 2 or 3°C. Shrimp do ontogenic migration: juveniles and young males are found in shallower waters at the head of the channels while the older females are mainly found in deeper water. Shrimp of all stages migrate vertically, leaving the bottom at night to rise in the water column to feed on plankton and then returning to the bottom during the day. It appears that the circulation of water masses in the St. Lawrence River is favourable to shrimp larva retention. However, horizontal distribution probably depends more on ecological factors affecting larva survival (Ouellet and Lefaivre 1994). Other factors, such as water temperature, can also explain shrimp distribution (Parsons and Fréchette 1989). Feeding occurs in both the benthic and pelagic environments, in accordance with their vertical migrations. Polychaetes, small crustaceans and detritus are the main prey during the day while copepods and euphausiids are the principal prey items during the nocturnal migration. Predation is the main cause of shrimp mortality. Greenland halibut (*Reinhardtius hippoglossoides*) progressively replaced cod (*Gadus morhua*) and redfish (*Sebastes spp.*) as the main shrimp predators in the early 2000s (Savenkoff et al. 2006). Moreover, just like snow crab populations, northern shrimp populations underwent an increase in abundance and distribution following the collapse in demersal fish stocks. In these layers, two other commercial species of interest are present, i.e., deepsea king crab (*Lithodes maja*) and the Stimpson's surfclam (*Mactromeris polynyma*).

3.4 FISH COMMUNITY

3.4.1 Marine fishes

The St. Lawrence system can be divided into two general fish habitats: the shelf areas and the deep channels, which support rather different, but seasonally intermingled communities. In general, diversity tends to decrease from the south (Cabot Strait) to the northwest (Estuary) and northeast (Strait of Belle Isle) areas for both the shelf and channel communities. Moreover, the nature of the bottom also has an influence: the Magdalen Shallows and west coast of Newfoundland shelves have primarily soft bottoms whereas Québec's north shore is mostly hard bottomed.

The shallows are characterized by warm surface waters and high productivity in summer. They are important spawning, nursery, and adult feeding grounds for large biomasses of both groundfish and pelagic fishes in these areas. The Magdalen Shallows also supports high densities of American plaice (*Hippoglossoides platessoides*) which, together with cod, constitute the dominant groundfish in the southern Gulf. In addition, the southern Gulf comprises important feeding grounds for a number of highly migratory fishes that move into the area to feed in summer, notably bluefin tuna (Thunnus thynnus) and spiny dogfish (Squalus acanthias).

In winter, the Shallows are typically ice–covered, with water temperatures near the freezing point of seawater (–1.5°C) from surface to bottom. To avoid these harsh winter conditions, many of the large fishes migrate out of the Shallows each winter. Some migrate far out of the Gulf to overwinter at more southerly latitudes (bluefin tuna, mackerel [Scomber scombrus] and spiny dogfish). Others migrate into warmer deep waters in the Laurentian Channel or along its slopes

[15] A randomly interbreeding population of individuals that mate at random, i.e., each individual is equally likely to mate with any individual of the opposite sex.

(adult herring [Clupea harengus], cod, white hake [Urophycis tenuis], American plaice, witch flounder [Glyptocephalus cynoglossus], and thorny skate [Amblyraja radiata]). Some of these species overwinter in these areas (American plaice, witch flounder) but others move towards the entrance of the Laurentian Channel in the Cabot Strait area (cod, herring, redfish [Sebastes spp.]. The main pathway for these fall migrations out of the Gulf and the return migrations each spring is along the west coast of Cape Breton Island.

In the northern Gulf, shallow shelf areas along the west coast of Newfoundland and along the Québec north shore represent important summer feeding grounds and nursery areas for both demersal and pelagic fishes (cod and herring). Herring along the west coast of Newfoundland move into the warm deep waters of the Esquiman Channel to overwinter. Like the southern Gulf population, cod in the northern Gulf is highly migratory, moving into warm deep waters in the Cabot Strait area in winter.

The relatively warm deep waters of the channels that dominate the northern Gulf constitute the feeding, spawning, and nursery grounds for a number of deepwater and slope species, notably the redfishes (*Sebastes mentella*, *Sebastes fasciatus*, and occasionally, *Sebastes norvegicus*), Greenland halibut (*Reinhardtius hippoglossoides*) and witch flounder. Adults of some of these species (witch flounder) move up the slopes to feed in somewhat shallower water in summer. These deep channels also constitute the overwintering grounds for the adults of many of the large–bodied fishes whose spawning, nursery and/or feeding grounds occur in shallower shelf waters (cod, herring, plaice, white hake, and thorny skate). Although the deepwater and slope species do not need to undertake major migrations to avoid harsh winter conditions, some appear to undertake seasonal movements.

The marine fish communities in the Gulf have experienced dramatic changes in the relative abundance of their component species over the last 30 years starting in the early 1970s. Many of the large–bodied groundfish declined to very low levels in the 1990s (cod, redfish, white hake, American plaice, skates) (CAFSAC 1994). On the other hand, many invertebrates and pelagic fishes were at relatively high levels of abundance throughout much of the 1990s and early 2000s (shrimp, crab, herring, and capelin). However, Savenkoff et al. (2005) showed that increased fishing mortality in the northern and southern Gulf of St. Lawrence may have countered the expected increase in biomass of some species, such as Atlantic mackerel, following the net decrease in groundfish biomass and the ensuing drop in predation. In contrast to most groundfish, abundance increased in the 1990s for some deepwater flatfishes, notably Greenland and Atlantic halibut (*Hippoglossus hippoglossus*). These increases reflect strong recruitment in the 1990s. In the southern Gulf, where there is a long time series of consistent trawl survey data, other dramatic changes in the ecosystem seem evident. A number of cold water species (e.g., Arctic cod [*Boreogadus saida*], polar [*Cottunculus microps*] and Arctic [*Myoxocephalus scorpioides*] sculpins) increased temporarily in the mid 1990s, during a prolonged period of cold bottom waters in the southern Gulf. But most notable has been an increase in the abundance of many small–bodied species in the late 1980s and the 1990s. These changes in species composition have resulted in a large shift in the biomass spectrum of the fish community in the southern Gulf, with declines in the biomass of large–size fishes and increases in small sizes (Savenkoff et al. 2007a).

The causes of these ecosystem changes are not yet fully understood. The decline in the abundance of large–bodied groundfish is thought to be mainly due to overfishing, though for some species (e.g., cod) declines in productivity also appear to play a role. Given its current low

productivity, no significant recovery of the Gulf cod stocks is expected at least for the northern Gulf stock, even in the absence of fishing (Dutil et al. 2003). Mackerel and herring were at very low levels in the mid to late 1970s, likely the result of heavy fishing in the late 1960s and early 1970s. The increase in the biomass of these pelagic fishes throughout the 1980s may reflect a recovery from overfishing following declines in their exploitation rates in the late 1970s. The recent increase in the abundance of small–bodied fishes in the southern Gulf may reflect a release from predation following the decline in large–bodied predatory fishes. Significant environmental changes have also occurred over 30 years beginning in the early 1970s. Bottom waters on the shelves were relatively warm in the late 1970s and early 1980s. The cold intermediate layer (CIL) in the Gulf underwent a prolonged cooling from the late 1980s to the mid 1990s. The Gulf of St. Lawrence region has experienced abnormally low water temperatures, particularly between 1990 and 1995 in the southern Gulf (Drinkwater et al. 1995). However, in the late 1990s and early 2000s, spring temperatures have been unusually warm, with 1999 the warmest spring in the 50–yr record. The effects of these environmental changes on the fish communities in the Gulf are not fully understood.

In addition to these changes in abundance, major shifts in distribution have occurred for a number of species over the period from 1971 to 2002. The distribution of cod on their feeding grounds in the southern Gulf appears to be density dependent, with distribution shifting offshore to intermediate depths at high abundance and to shallow inshore waters at low abundance. The timing of the fall migration of cod to overwintering grounds appears to have shifted to earlier dates during the 1990s. The distribution of capelin has expanded into the southern Gulf during the 1990s and early 2000s, covering much of the Magdalen Shallows in September; these fish had a much more restricted distribution in the southern Gulf over most of the years between 1971 and 1990. Increased capelin abundance is typically associated with lower than normal ocean temperatures but not with warmer than normal conditions (Frank et al. 1996). Beginning in the late 1980s or early 1990s, there has been an eastward shift in the September distribution of a number of groundfish species (cod, plaice, white hake, witch flounder, thorny skate). The cause of this shift is unknown. One possibility is that it is related to the pronounced cooling of the western Magdalen Shallows in the late 1980s and early 1990s.

3.4.2 Diadromous fishes

Diadromous fishes are fish that migrate between marine and freshwater (McDowall 1987). Within this group, anadromous fishes, of which there are nine species (identified further in the text) in the Gulf of St. Lawrence, spawn in freshwater and migrate to sea to feed and mature. Catadromous fish spawn in salt water and utilize freshwater for feeding and growth. The single catadromous species in the St. Lawrence system, the American eel (*Anguilla rostrata*), utilizes the freshwater and estuarine areas for growth and maturation but spawns as a panmictic[15] unit in the mid–Atlantic area.

There is a notable south to north cline in diversity and abundance of these species within the Gulf. The southern portion of the Gulf of St. Lawrence is the northern limit of the spawning populations of several anadromous fish species including three species of anadromous clupeids (alewife [*Alosa pseudoharengus*], blueback herring [*Alosa aestivalis*], and American shad [*Alosa sapidissima*]), and striped bass (*Morone saxatilis*). The Gulf of St. Lawrence includes the largest populations of Atlantic salmon (*Salmo salar*) and anadromous rainbow smelt (*Osmerus mordax*) in eastern North America.

Some of the diadromous species have a restricted distribution within the Gulf of St. Lawrence. Sea lamprey (*Petromyzon marinus*) spawning runs are most concentrated in the southern Gulf of St. Lawrence (Beamish 1980). There are spawning runs of alewife and blueback herring in the majority of the rivers in the Gulf (DFO 2001). Spawning runs of American shad appear restricted to the Northwest Miramichi and Southwest Miramichi rivers of the Gulf and in the St. Lawrence River although shad occur in numerous estuaries and ascend other rivers of primarily the southern Gulf (Chaput and Bradford 2003). There is one spawning population of striped bass in the Northwest Miramichi, and the coastal feeding distribution appears limited to the southern Gulf from the western coast of Cape Breton west to the tip of the Gaspé peninsula (Douglas et al. 2003). There remains one confirmed spawning location for Atlantic sturgeon (*Acipenser oxyrhynchus*) in the St. Lawrence River near Québec City (Hatin et Caron 2002). No spawning populations have been confirmed in the Gulf, and returns of tags from Newfoundland, Labrador and southern Gulf fisheries of sturgeon tagged in the St. Lawrence River suggest that it is the principal if not sole source of sturgeon occurring in the Gulf.

Beside, Atlantic salmon is widely distributed in rivers bordering Québec, Newfoundland, and Maritime provinces of the St. Lawrence system (O'Connell et al. 1997). Individual river run sizes are generally small, but four rivers (Northwest Miramichi River, Southwest Miramichi River, Restigouche River, Humber River) are receiving more than 10,000 individuals in a given year.

Cabot Strait and the Strait of Belle Isle are important migratory corridors for the diadromous fishes. On the basis of the timing of the commercial fisheries and tagging programs, the anadromous clupeids are assumed to enter and exit the Gulf through Cabot Strait, exclusively along the north of Cape Breton Island and disperse westward north of PEI and through Northumberland Strait (Rulifson and Dadswell 1987). The Cabot Strait area is a common migration pathway for seven of the ten diadromous species in the Gulf of St. Lawrence. The Strait of Belle Isle is considered a more important migration corridor for Atlantic salmon from the rivers along the northern portion of the St. Lawrence system (Newfoundland, Québec's North Shore). Migration into and out of the Gulf occurs predominantly during the months of May to November. The Strait of Belle Isle is also used by some species and life stages to enter and exit the Gulf.

In terms of landings in the Gulf, the gaspereau (alewife) and blueback herring fisheries are presently the largest, followed by smelt, eel, tomcod and shad (Leblanc and Chaput 1991). The recreational fisheries catch of Atlantic salmon in eastern Canada has been on the order of 100,000 fish annually in recent years, with more than half the catch occurring in Gulf of St. Lawrence rivers.

3.5 MARINE MAMMALS AND LEATHERBACK TURTLE

3.5.1 Whales

There are two groups of whales or cetacean suborders: the Mysticeti, whales with baleens, and the Odontoceti, whales with teeth. The toothed whales are usually much smaller than the baleen whales.

Mysticeti

In the Estuary and Gulf of St. Lawrence, there are five species of baleen whales: finback whale

(*Balaenoptera physalus*), minke whale (*Balaenoptera acutorostrata*), blue whale (*Balaenoptera musculus*), humpback whale (*Megaptera novaeangliae*) and the northern right whale (*Eubalaena glacialis*). The northern right whale is generally found in the Bay of Fundy and the Gulf of Maine. However, since 1995, right whale sightings have been increasing in the St. Lawrence. A population of grey whales (*Eschrichtius robustus*) was historically present in the Gulf of St. Lawrence, but this group was extirpated before the end of the 1800s by commercial whaling and was designated as such in 1987.

Odontoceti

Eight species of Odontoceti can be observed in the St. Lawrence. These are beluga (*Delphinapterus leucas*), long finned pilot whale (*Globicephala melas*), white–sided (*Lagenorhynchus acutus*) and white–beaked (*Lagenorhunchus albirostris*) dolphins, and harbour porpoise (*Phocoena phocoena*); killer (*Orcinus orca*) and sperm (*Physeter catodon*) whales can also sometimes be spotted in the St. Lawrence (Leatherwood et al. 1976). While the northern bottlenose whale (*Hyperoodon ampullatus*) is fairly common in the deeper waters off the coast of Nova Scotia and Labrador, it is extremely rare in the Gulf.

Marine mammals feed at most trophic levels, from plankton to predatory fish, and they even feed on other marine mammals. The toothed whales (Odontoceti) as well as pinnipeds are carnivorous and their diets consist of pelagic, demersal or benthic fish, cephalopods and crustaceans, pelagic or benthic shrimp, worms, molluscs, mammals and birds (Fontaine 1998).

One of the major food sources of the baleen whales (Mysticeti) is zooplankton. Some species like the blue whale feed almost exclusively on planktonic crustaceans that are very similar to shrimps but that belong to the Euphausiacae or krill family. Other species have been known to eat, in addition to krill, copepods (Calanidae), molluscs (squid), small fish (capelin, smelt, sand lance and Arctic cod) and the juveniles of bigger fish such as herring and mackerel (Fontaine 1998).

Significant concentrations of phytoplankton and a relatively high secondary productivity occur in the St. Lawrence Estuary. Between Tadoussac and Les Escoumins, the Laurentian Channel ends abruptly at the confluence of the Saguenay Fjord, resulting in an upwelling of cold mineral–rich water under effects of strong tidal circulation (very rich area). This area also has a significant accumulation of biomass of foraging species, such as euphausiid crustacean species (krill) and capelin. In fact, this area was found to be one of the richest krill aggregations in the Northwest Atlantic (Simard and Lavoie 1999). Juvenile capelin also aggregate over the shallows at the channel head during the summer period (Simard et al. 2002). This is especially notable at the Saguenay entrance. Other species such as shrimp and juvenile sand lances are abundant and are prey for a wide variety of marine mammals (Runge and Simard 1990).

The impressive concentrations of foraging species at the head of the Laurentian Channel in the St. Lawrence Estuary create vital feeding habitats for many large cetaceans. Several species migrate to this region over the course of the summer to feed and then return to warm southern waters during winter to mate and give birth. Species such as the minke whale, which overwinter in Bermuda and the West Indies, return and feed in the Estuary (Clark 1994). The St. Lawrence Estuary is also a critical habitat for the St. Lawrence beluga and harbour seals since they are the only species that spend their entire life cycle there.

The Cape Breton Trough near Cheticamp, NS, is also an important foraging area for various

cetaceans. This area features large canyons, which appear to be areas of high productivity, leading to large concentrations of food for marine mammals. The Strait of Belle Isle has currents and tides that favour concentrations of krill, this attracting many cetaceans for feeding. Humpbacks move north through the Strait in early fall to feed on spawning herring. Fin whales seem to move south through the Strait in the summer and fall. Southeast Prince Edward Island and the Îles–de–la–Madeleine are also two areas of importance for seals and whales. Cabot Strait, off Cape Breton, is also an important migratory corridor for marine mammals moving in and out of the Gulf of St. Lawrence (Kingsley and Reeves 1998).

3.5.2 Seals of the St. Lawrence

Seven species of seals or pinnipeds are known to frequent the Estuary and Gulf of St. Lawrence; however, only four are common. These are harp seals (*Phoca groenlandica*), hooded seals (*Crystophora cristata*), harbour seals (*Phoca vitulina*), and grey seals (*Halichoerus grypus*). These four species are members of the phocid seals group, also known as true or hair seals. Harp and hooded seals are migratory species whereas the harbour and grey seal are year–round residents of the St. Lawrence. Ringed seals (*Phoca hispida*) and bearded seals (*Erignathus barbatus*) are occasional visitors to the northern parts of the Gulf where there is an active hunt for these two species. Atlantic walrus (*Odobenus rosmarus rosmarus*) was historically found in the Gulf but has been extirpated by commercial sealers from the Gulf, the last one taken from Îles–de–la–Madeleine in the 1700s (Lesage et al. 2001). There are occasional reports of walrus sightings but these are most probably vagrants.

Over the last 50 years, a reduction in harvesting activity has permitted many pinniped populations to increase. However, there is still an important harp seal hunting activity in areas of the St. Lawrence. A small number of grey seals are also captured every year in the Gulf. The hooded seal herd is small and hunting of this population as well as the harbour seal population is prohibited.

It is evident that seals consume large quantities of fish in eastern Canadian waters. —In one study, 77% (by weight) of the total prey consumed by grey, hooded, and harp seals in Atlantic Canada consisted of fish, of which capelin and sandlance were the dominant species, accounting for 49% of the total fish consumed by seals (Hammill and Stenson 1997). Major commercial species such as cod form a relatively minor component in the overall seal diets (Savenkoff et al. 2004). Harp seals were the most important seal predator, accounting for 82% of the total fish consumption. Hooded seals and grey seals also consumed significant quantities of fish, accounting for 10% and 8% of the fish consumed respectively. Harbour seals consumed insignificant quantities of fish, accounting for less than 1% of the total consumption of prey by seals.

3.5.3 Leatherback turtles (*Dermochelys coriacea*)

There are seven species of marine turtle worldwide; of these, two are known to range into Atlantic Canadian waters: the leatherback turtle (*Dermachelys coriaea*) and the loggerhead turtle (*Caretta caretta*). Only the leatherback turtle is currently considered to occur in the Gulf of St. Lawrence.

Adult leatherbacks are highly migratory and are known as the most pelagic of all sea turtles. However, in Canada they can be regularly observed along the continental shelf (James 2000 in COSEWIC 2001). Leatherbacks normally inhabit areas where coelenterate (i.e., jellyfish)

productivity is high, along oceanic frontal systems and along vertical gradients located at oceanic fronts (Lutcavage 1996 in COSEWIC 2001). Therefore, the leatherback's habitat may be strongly related to prey availability, with turtles moving from the offshore waters into the coastal areas to take advantage of the seasonal proliferations of jellyfish (COSEWIC 2001).

Since leatherback turtles have experienced a dramatic population decline of more than 60% since 1982 (based on counts of nesting females), this species is considered endangered by COSEWIC (Committee on the Status of Endangered Wildlife in Canada) and as such is listed in Schedule 1 of SARA (Canada's Species at Risk Act) (COSEWIC 2001). The major threat to the leatherback turtle in the Gulf of St. Lawrence is that of entanglement in fishing gear, which can result in death by drowning or serious injuries. Marine debris is problematic because adult leatherbacks often mistake floating garbage for jellyfish (for example, plastic bags). Ingestion of such materials inevitably results in death (COSEWIC 2001).

3.6 MARINE BIRDS

The Gulf of St. Lawrence is home to various species of birds that depend on the resources of the coast and sea to survive. Some of these birds breed on rocky islands and cliffs and forage the sea for their food; others breed on land or in freshwater only to return to the sea afterwards. The birds can be divided into four different groups: inshore birds, offshore or pelagic birds (these two groups combined are also known as seabirds), waterfowl and shorebirds.

In general, birds and marine mammals play important roles in the marine food webs. Seabirds, marine mammals and large fish share the upper ranks of the food chain. In the Gulf of St. Lawrence, there are approximately 18 different species of breeding seabirds (inshore and offshore). We also find various species of shorebirds that are usually present in the coastal zone for only a brief period each year. It is estimated that 90% of the prey consumed by seabirds are fish (mainly pelagic) and squid with the remaining 10% is divided between benthic and pelagic invertebrates (Cairns et al. 1991).

Offshore (pelagic) birds spend long periods of time away at sea where they obtain all or most of their food requirements. Pelagic birds, including petrels and auks, for example, are independent of land for both feeding and resting and will feed over deep water in the offshore zones. These pelagic birds will exploit various food sources that can range from plankton to various species of small fish. However, they all depend on land for breeding. These breeding sites are usually rocky cliffs and islands[16]. Inshore birds feed in the inshore habitats where food is found on or near the bottom of shallow water. These birds (cormorants, gulls, terns) will normally return to land to spend the night.

Large numbers of breeding seabirds are found around the Gaspé Peninsula and along Québec's north shore; approximately one–third of all Gulf of St. Lawrence seabirds nest in each of these areas. Bonaventure Island hosts ten species and three quarters of all Gaspé Peninsula breeding seabirds. On Québec's north shore, the presence of productive Labrador waters entering the Gulf through the Strait of Belle Isle makes this area attractive to seabirds.

Seabird numbers are lowest in western Newfoundland and the southern gulf. These two regions

[16] Nettleship, N. 1980. A guide to the major seabird colonies of eastern Canada–identity, distribution and abundance. Unpubish Report, Canadian Wildlife Service–Seabird Research Unit, Dartmouth, NS.

have scarce or low quality breeding habitats (for examples, few offshore rocky islands featuring cliffs). The low numbers of birds on the cliffs of western Cape Breton may be linked to oceanographic conditions rather than the lack of habitat (Cairns et al. 1991, Lock et al. 1994). However, by fall, after the end of the breeding season, the pelagic or offshore seabirds have dispersed from the colonies and can be found in their greatest density in the well–mixed and productive waters in Cabot Strait. Their distribution in winter depends on the movements and extent of the ice cover, which therefore makes it difficult to predict their location (Lock et al. 1994).

Populations of herring gulls had been increasing rapidly in the 70s and 80s throughout the Gulf of St. Lawrence, but since the end of the 80s, the trend has reversed. It has been suggested that the decline of the herring gull could be related to a decrease in the availability of fish offal, following the collapse of the cod fishery (Chapdelaine and Rail 1997). The latest (stable) trend between 1993 and 1998–99 on the north shore suggests that herring gull populations are perhaps back to more "natural" levels there. Black–legged kittiwake numbers have also been declining throughout the Gulf since the end of the 80s, and there is no indication of stabilization yet. In contrast, the breeding population of northern gannets has increased more than threefold in the past 30 years in the GSL, where it is now the second most abundant seabird. Also, populations of alcids, which were at very low levels in the 70s, have recovered steadily and at a fast rate since. The most recent trends, however, indicate that the largest colonies of common murres have tended to stabilize on the north shore (1993–1999) and at Bonaventure Island (1989–2002), and that the Atlantic puffin decreased sharply and unexpectedly at all major concentrations on the north shore (1993–1999). Common eider numbers also underwent a spectacular recovery in north shore bird sanctuaries in the 80s and 90s.

The general and rapid increase of species such as the alcids (the razorbill, the common murre, the Atlantic puffin and the black guillemot) suggests a possible increase in the supply of forage fish such as sand lance and capelin, which may have a positive effect on the breeding performance of these birds (Chapdelaine and Brousseau, 1991, 1992, Chapdelaine 1995). The changes in the abundance of these small prey fish may be related to the decrease in the number of large predators, such as the Atlantic cod, due to overfishing (Chadwick and Sinclair 1991). If we combine this with the declines in herring gulls and black–legged kittiwakes, which are possibly associated with the collapse of the cod fishery (through a diminution in fish offal and discards), it appears that human exploitation of marine resources in the Gulf of St. Lawrence may have resulted in important changes in the seabird community. Overall in the last 20 years, offshore birds and diving species have been increasing considerably, whereas inshore birds and surface–feeders have declined.

4.0 SOME ELEMENTS OF THE GULF ECOSYSTEM DYNAMICS

Although an effort was made to indicate some important physical oceanographic processes in relation to particular biological properties in the previous sections, they were mostly concerned with a basic description of the system components. In this section, a succinct overview of the system dynamics will be presented to highlight the particular functionality of the Gulf ecosystem.

4.1 SEASONAL BIOLOGICAL PRODUCTION CYCLES

Except for the Lower St. Lawrence Estuary and the Maximum Turbidity Zone area in the Upper

Estuary, light intensity does not appear to be a limiting factor for primary productivity in the entire Gulf of St. Lawrence (Therriault and Levasseur 1985). Instead, nutrients, essentially nitrate availability, are identified as the primary driver of the spring phytoplankton blooms over the entire Gulf as well as for sporadic and/or season–long production events at specific sites. In fact, the documented strong spatial and temporal variability of the planktonic production were clearly reproduced through nutrient variations in response to sea–ice dynamics, runoff, tidal, and wind–induced circulation, and wind mixing in a coupled physical–biological model of the planktonic production (Le Fouest et al. 2005).

The average picture for the entire Gulf is that late fall and winter deep vertical convection homogenize the water column (down to ca. 100 m), creating a standing stock of nutrients (nitrates) in the upper layer that varies inter–annually as a function of variations in the atmospheric conditions (Plourde and Therriault 2004). In addition, stochastic atmospheric events, such as late fall wind storms passing over the Gulf, can also create intense vertical mixing and contribute to high winter nitrate concentration in the upper layer (M. Starr, Maurice-Lamontagne Institut, Mont-Joli, QC, personnel communication). In a recent simulation study, Le Fouest et al. (2005) presented a general view of the seasonal production cycle in the Gulf of St. Lawrence. The diatom–dominated vernal bloom occurs (ca. second half of April) following sea–ice melt or retreat, which increases stratification and the light level. The decline of the vernal bloom results from nitrate depletion in the euphotic zone and possibly increasing grazing pressure from the mesozooplankton. During summer and fall, large phytoplankton cells and mesozooplankton biomass gradually decrease, but the model suggests that small phytoplankton cells and microzooplankton vary little throughout the year.

In the previous description of the physical and plankton conditions of the Gulf, specific regions were identified as zones of important vertical mixing of water masses and productivity "hot spots": 1) the head of the Laurentian Channel in the Lower Estuary (also the heads of Anticosti and Esquiman channels); 2) the tidal mixing at the Jacques Cartier Strait and Strait of Belle Isle; 3) the upwelling along Québec's north shore and Anticosti's south coast; 4) the north-western Gulf caracterized by a high variability due to a cyclonic structure, the Anticosti Gyre, and the Gaspé Current. The precise physical mechanisms involved at these sites were reviewed in the previous section. How these features may be responsible for particular regional zooplankton (and higher trophic levels) communities is important for our understanding of the functioning of the Gulf system. Ultimately, it must be remembered that the entire Gulf of St. Lawrence can only be understood as the dynamic interactions of all the regional differences in productivity and plankton community structures. Although it may be convenient to divide the Gulf into distinct biogeography units (de Lafontaine et al. 1991), much effort is still required before we can produce the comprehensive integration of all the dynamic subsystems that define the Gulf of St. Lawrence Ecosystem.

4.2 LOWER ESTUARY–GASPÉ CURRENT–SOUTHWESTERN GULF COMPLEX

Probably the best studied ecosystem of the Gulf is the Lower Estuary–Gaspé Current–southwestern Gulf (Magdalen Shallows) complex. The "nutrient pump" at the head of the Laurentian Channel supports a relatively high productivity in this region. Noticeably, the spring bloom in the Lower Estuary is delayed by 4 to 8 weeks relative to the open Gulf. The optimal environmental conditions to initiate this main bloom appear when the spring runoff subsides. An increased retention time seems to be the mechanism that allows the spring bloom to occur in the

Lower Estuary (Zakardjian et al. 2000). Environmental conditions in the Lower Estuary and Gaspé Current generally allow two or three blooms annually. One or two short and less intense blooms occur in mid–May and/or mid–August. A more intense bloom occurs at the end of June or in early July (Starr et al. 2003). The influence of the Lower Estuary is responsible for high but also variable concentrations of nutrients in the Gaspé Current that support an intense phytoplankton production that may last until the end of June and sometimes later (Starr et al. 2003).

Also important in the Lower Estuary is that an increase in stratification, temperature and nutrients in the water column as well as lower salinity in surface waters all favour the occurrence of the toxic algae blooms (Therriault et al. 1985, Weise et al. 2002). Blooms of the toxic alga *Alexandrium tamarense* were found in the plumes of the Manicouagan and Aux Outardes rivers and in the Gaspé Current (Therriault et al. 1985). *Alexandrium* cysts and cells at the mouths of these rivers may serve to inoculate other blooms that appear along the southern coast of the Gulf of St. Lawrence along the Gaspé Peninsula (Blasco et al. 1996).

The high production in the Lower Estuary supports an abundant zooplankton community. The life cycle of zooplankton creates seasonal differences in biomass and community structure. Many species of copepods are herbivores/omnivores that require good timing between their activities and the abundance of phytoplankton. The Lower Estuary and Gaspé Current are important regions for the reproduction of copepods but also for the transport of the biomass toward the southern Gulf region. Thus, the reproductive and developmental period for *C. finmarchicus* is tightly coupled to the local spring or summer–depending on the region–phytoplankton bloom. In the Lower Estuary, the greatest abundance of female *C. finmarchicus* is observed at the end of spring or early summer, when they may take advantage of the high phytoplankton biomass to complete maturation and produce their eggs (Plourde and Runge 1993, Plourde et al. 2001).

The observed seasonal variations in copepod community structure seem also to be linked to the magnitude of the flushing of small species (e.g., *Oithona spp.*, *Acartia spp.*) in surface waters and copepod developmental stages at the start of the species–specific reproductive periods (Plourde et al. 2002). The intensity of the spring and summer outflows thus influences the relative proportion of young stages of the genus *Calanus* and other organisms like euphausiids that are retained in the region or exported to other regions in the Gulf of St. Lawrence. Thus the mesozooplankton community in the spring and part of the summer is dominated by species of the genus *Calanus*. At the end of summer and in autumn, when the *Calanus* population enters hibernation and moves into deeper water, this community evolves towards one dominated by small species that are adapted to take advantage of the warmer surface waters (Plourde et al. 2002).

Interannual variations in copepod community structure (Plourde et al. 2002) and in the population dynamics of *C. finmarchicus* and *C. hyperboreus* have also been described for the Lower Estuary (Plourde et al. 2001, 2003). Although some links between phytoplankton blooms and abiotic factors (e.g., freshwater discharge, surface water heating, nutrient cycles) are evident, for the most part the mechanisms that account for interannual variation of zooplankton communities remain largely unknown. For example, how was the cooling period at the start of the 1990s linked to the increase in abundance of *Metridia longa* and decrease in abundance of *C. finmarchicus* in the Lower Estuary (Plourde et al. 2002)? The abundance of *Meganyctiphanes norvegica* (krill), *Thysanoessa raschii*, and *T. inermis* has also been observed to have decreased in the Lower Estuary since 1994. The proportion of krill in the zooplankton has decreased from

80% to 40% in less than 10 years. In addition, the reduction in the southern Gulf has been noticeable since 1987 and seems to reflect a general phenomenon that extends along all costal zones in Atlantic Canada (Harvey and Starr 2005).

The Gaspé Current is the extension of the flow from the Lower Estuary and leads to the Magdalen Shallows and the southern branch of the Laurentian Channel. This current export Estuary production toward the southern part of the Gulf resulting in large phytoplankton biomass and blooms that may last for several weeks (de Lafontaine et al. 1991, Starr et al. 2003). The dominant zooplankton species in this community are large copepods and euphausiids as well as small copepods (*Acartia spp.*, *Oithona spp.*) and developmental stages of large copepods (mainly *Calanus spp.*) exported downstream, hence a source for the local Calanus population in the southern Gulf (see below). Some studies have shown that the concentration of immature copepod stages in the Gaspé Current may reach abundances 10 to 20 times greater than those observed in the northwest of the Gulf (Fortier et al. 1992).

Under the influence of the Gaspé Current, the Magdalen Shallows does not support communities of large *Calanus* copepods, which are likely to be seeded each year in spring and/or summer. All development stages of large copepods such as *Calanus spp.* can be transported from upstream region, which would entirely (e.g., *C. hyberboreus*) or partly contribute to their high abundance and biomass in the region in addition to their local development in summer (e.g., *C. finmarchicus*). This transport is accomplished via surface circulation in the spring from deeper areas of the Gulf of St. Lawrence, in contrast to other species of copepods that are retained in the region (Runge et al. 1999, Zakardjian et al. 2003). For example, it is possible to observe interannual variations in the summer biomass of zooplankton that are largely due to variations in the biomass of organisms greater than 1000 µm in length (Runge et al. 1999). In this region, the abundance and diversity of zooplankton, including ichthyoplankton, appear superior to those recorded elsewhere in the Gulf of St. Lawrence (de Lafontaine et al. 1991). However, that view may change as the sampling effort in the northern and northeastern Gulf intensifies, under the AZMP (Atlantic Zonal Monitoring Program) for example. The copepod community differs from that in other regions in the Gulf of St. Lawrence. Other than copepods of the genus *Calanus* (mostly *C. finmarchicus*), most of the dominant species are small and include *Temora longicornis*, *Centropages spp.*, and *Tortanus discaudatus* (de Lafontaine et al. 1991). In the southeastern Gulf, the greatest biomass of zooplankton is found in the western portion of the Magdalen Shallows (Shediac Station) where strong and persistent concentrations of chlorophyll have been observed in some years (Drinkwater and Pepin 2003).

The abundance and production of zooplankton have a major influence on the survival of ichthyoplankton and the recruitment of fish species. For example, high mackerel recruitment appears to be linked to high copepod egg production (Ringuette et al. 2002, Plourde and Castonguay 2005). A similar hypothesis was suggested by Runge and de Lafontaine (1996), who showed a link between the abundance of copepod (*Calanus spp.*) eggs and redfish larvae at stations in the northeastern Gulf (southeast of Anticosti Island).

4.3 NORTHWESTERN GULF (ANTICOSTI GYRE)

Another part of the Gulf that has historically received attention from the scientific community is the northwestern Gulf or Anticosti Gyre region. Although it is treated as a distinct entity, that region is also closely connected with the adjacent Gaspé Current. The Gaspé Current is sometime unstable and separates from the coast to partly recirculate in the northwestern Gulf

(Saucier et al. 2003), with significant impact on the phytoplankton biomass distribution in the area (Le Fouest et al. 2005). The region can also receive early life stages of Calanus from the Lower Estuary (Zakardjian et al. 2003). This region is crossed by a portion of the Laurentian Channel; hence deep–water upstream current could play a role in the distribution and the structure of the zooplankton community in the Lower Estuary (see below). The circulation in that region creates a quasi–permanent eddy known as the Anticosti Gyre. This allows nutrients to be concentrated when the waters become the less stratified in the spring, permitting a very short but intense diatom–dominated bloom. Although this region with the Anticosti Gyre is recognized as being less productive than the southern Gulf, the concentration of chlorophyll there is greater in the spring (Starr et al. 2003). The depletion of nutrients occurs two to three weeks earlier than in the southeast Gulf, suggesting that the spring bloom starts earlier there (Starr et al. 2002). Following the bloom, nutrients in the strongly stratified and shallow surface waters at the centre of the Gyre become depleted during the summer, thus limiting phytoplankton productivity.

The deep Laurentian Channel and the influence of water masses of various origins (e.g., Arctic, Atlantic) promote the presence of euphausiids, chaetognaths (*Sagitta elegans*), hyperiid amphipods, and gelatinous organisms (siphonophores). Although *Oithona similis* represent a large proportion of the abundance of the community, the large copepods of the genus *Calanus* are also abundant and contribute greatly to the high total zooplankton biomass in the region. The great depth (320 m) favours the presence of copepods of the genus *Calanus* (*C. finmarchicus*, *C. glacialis*, and *C. hyperboreus*) that spend a considerable part of the year in diapause in deep waters. The abundance of these species in the Anticosti Gyre accounts for the great biomass of zooplankton there, especially in the autumn. Late developmental stages of *Calanus spp.* present in the deep waters of the Laurentian Channel in the autumn are subsequently transported by the deep current towards the head of the Laurentian Channel in the Lower Estuary. As observed for the genus *Calanus*, krill may similarly be transported by deep–water currents to the head of the Laurentian Channel, where mature individuals are concentrated. This transport mechanism may create the greatest concentration of krill (mostly *Meganyctyphanes norvegica* and *Thysanoessa rashi*) observed in the northwest Atlantic (Simard et al. 2002).

The abundance and diversity of the ichthyoplankton have been reported low and dominated by capelin and redfish (de Lafontaine et al. 1991). That may be the case for the Anticosti Gyre itself; however, in the mid 1980s, high concentrations of fish eggs (cod, witch flounder) and larvae (sandlance, redfish) were observed along the Québec coast, southwest Anticosti Island and in Jacques Cartier Strait (Ouellet et al. 1994). Furthermore, the northwestern Gulf is an important zone for larval development in the spring and for the recruitment of northern shrimp (*P. borealis*) (Ouellet et al. 1990, Ouellet and Lefaivre 1994).

4.4 NORTHEASTERN GULF

The data for this region are still fragmentary but they have been improved over the past few years with the implementation of the AZMP. The main characteristic of the northeastern Gulf is the influence of the incursion of cold, salty water from the Labrador Shelf coastal current through the Strait of Belle Isle (especially in winter). The phytoplankton biomass observed there suggests that this region of the Gulf of St. Lawrence is less productive than the Estuary and northwestern region (de Lafontaine et al. 1991, Starr et al. 2003,). Recent simulation reveals nevertheless possible high production events along the Québec coast associated with Labrador Shelf water entering through the Strait of Belle Isle in late summer and fall (Le Fouest et al.

2005). Wind–induced upwellings along the Québec coast may also cause episodic enrichment of surface waters. The large channels in the area (Esquiman, Anticosti) promote the development of a great biomass of zooplankton at their margins. The large copepods *C. finmarchicus* and *C. glacialis* dominate these communities (de Lafontaine et al. 1991, Harvey et al. 2004).

The entrance of the Esquiman Channel is also an important spawning site for the northern Gulf cod stock (Ouellet et al. 1997). A diverse ichthyoplankton community, dominated by capelin and herring larvae, has been observed in summer on the west coast of Newfoundland (Grégoire et al. 2006).

4.5 RECENT CHANGES IN THE GULF OF ST. LAWRENCE

The Gulf of St. Lawrence has been subject to large–scale climate–driven changes through the years that can have impacts on the entire ecosystem. For example, a major hydrodynamic shift has recently occurred in the Gulf. The hydrological data recorded since 1996 shows the increased incursion of cold water from Labrador Shelf through the Strait of Belle Isle, especially in 2000 and 2001 (Therriault et al. 2002). This input of cold, dense, water partly of Arctic origin into the Gulf of St. Lawrence may have numerous physical and biological repercussions, for example, the appearance of the diatom *Neodenticula seminae* in the Gulf of St. Lawrence during the spring bloom of 2001. This diatom is atypical in the Gulf and is normally found in northern Pacific waters. One hypothesis to explain this re–introduction is that the species was entrained in a water mass from the Pacific Ocean that was advected into the Arctic Ocean and then into the the Gulf transiting by the Labrador Current. It proliferated in the Lower Estuary and Gulf in 2001 and in 2002 (Starr et al. 2003). Similarly, the increase in the abundance of the hyperiid amphipod *Themisto libellula* in the Gulf of St. Lawrence could be associated with the intrusion of Labrador Shelf water during the winter at the Strait of Belle Isle. There is no mention of this arctic species in the Gulf of St. Lawrence in the literature or in samples collected in the Gulf of St. Lawrence before the start of the 1990s. Harvey et al. (2004) found a correlation between the abundance of the species and the proportion of Labrador coastal current waters in the CIL that passed through the Strait of Belle Isle. When abundant, that predatory species could have an impact on mesozooplankton biomasses in the entire ecosystem.

4.6 MARINE FOOD WEB DYNAMICS

Changes in many marine ecosystems have no doubt occurred, but efforts to model their holistic dynamics have not yet been successful. The various subsystems can be modeled with some success to produce a "snap shot" state for a certain period, but putting the various subsystems together in the context of temporal and spatial variation is more complex (Larkin 1996). The difficulty lies partly in the number of variables and the way in which only small errors in their estimation may lead to large uncertainties or inaccuracies at spatial and temporal scales. Compounding the problem is the lack of data for all trophic levels at all spatio–temporal scales. Modeling of large marine ecosystems is still in its infancy and represents simplifications of the trophic interactions in the system. Moreover, the validity of any conclusion regarding the ecosystem being studied depends on the input data (and the confidence that we have in them). Even though most of the data are good estimates for the specific ecosystem studied, some input values are rough estimates only, meaning that these values are assembled from different literature sources and not from independently measured parameters. Some errors in parameter estimates could significantly alter the system's biomass budget, especially for the most important

species of the ecosystem, or produce a totally different solution. This illustrates the need for further work to improve the input parameters in order to enhance the quality of future modeling efforts.

Conventionally, a distinction is drawn between bottom–up and top–down control in food web ecology (Hunter and Price 1992, Fath 2004). The bottom–up hypothesis asserts that primary producers influenced by environmental changes are the source of system regulation. An increase in productivity at the bottom of the trophic system leads to an increase in the productivity and abundance at all higher trophic levels. In contrast, the top–down hypothesis states that keystone species at a higher trophic level regulate the system. Effects of direct (consumption of prey by predators) or indirect (change in behaviour or morphology of the prey) predator–prey interactions may cascade through the food web (Carpenter et al. 1985, Pace et al. 1999, Romare and Hansson 2003). Effects of fishing are called top–down effects because their impact is most commonly at the top of the food chain. Effects of changes in the ocean environment are referred to as bottom–up effects because they influence the primary processes of production and take effect up through the food chain. Strong bottom–up effects should result in a positive correlation between predator and prey abundance because both populations depend on factors that regulate productivity (Worm and Myers 2003). On the other hand, strong top–down effects should result in a negative correlation between predator and prey because predators suppress prey abundance.

Piscivory (feeding on fish) is a common phenomenon in aquatic and marine ecosystems. Piscivory is the largest source of fish removals (mortality by predation) in most marine ecosystems, usually larger than fishery catches (fishing mortality) (Sissenwine 1984). Studies from marine ecosystems showed shifts in biomass flows after major perturbations such as intensive fishing (Jackson et al. 2001, Link and Garrison 2002, Bundy 2005). A recent analysis of historical data from the Scotian Shelf provides evidence of a trophic cascade from cod and other large predators through small fish, crab and shrimp, zooplankton and phytoplankton, to the level of nutrients (Frank et al. 2005). The cascade involved four trophic levels and nutrients and was driven by changes in the abundance of large predators of fish and macroinvertebrates (Figure 4). Large piscivorous predators declined dramatically, but their prey (herring, capelin, shrimp, and snow crab) increased in abundance. Frank et al. (2005) suspect that this shift in ecosystem structure is not unique because several cod stocks occupied similar oceanographic regimes in the northwest Atlantic (north of 44°N latitude).

Many Atlantic cod and groundfish stocks in the Northwest Atlantic, where they were the dominant predators, collapsed in the early 1990s and failed to respond to complete cessation of fishing (Rice and Rivard 2003). In fact, works of Savenkoff and colleagues (2007a, b) in the northern and southern Gulf support the top–down control hypothesis and they have shown evidence of a fishery–induced regime shift in the food webs of the two Gulf subecosystems. In both the northern and southern Gulf of St. Lawrence, ecosystem structure shifted dramatically from one previously dominated by long–lived, piscivorous groundfish (cod, redfish) and small–bodied forage species (capelin, mackerel, herring, and shrimp) during the mid–1980s to one now (beginning 2000s) dominated by small–bodied forage species and marine mammals as predators (CDEENA 2003, Savenkoff et al. 2007b). Moreover, based on a meta–analysis of time series data across nine regions in the North Atlantic, Worm and Myers (2003) calculated strong inverse correlations between shrimp and cod that they interpreted as "top–down" effects.

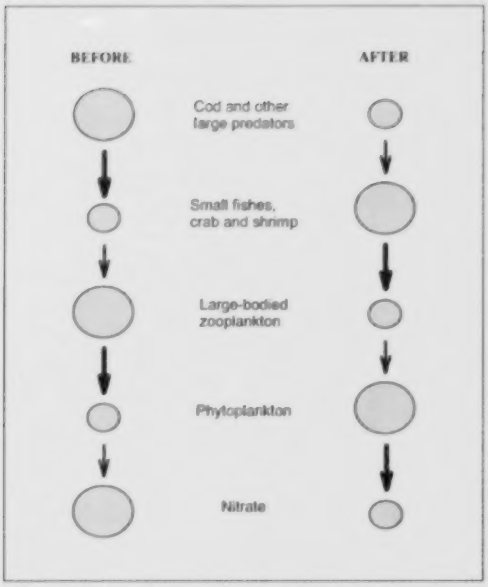

Figure 4. Cascading effect of the collapse of cod and other large predatory fishes on the Scotian Shelf during the late 1980s and early 1990s. The size of the circles represents the relative abundance of the corresponding trophic level. The arrows depict the inferred top–down effects. From Scheffer et al. (2005).

Ecosystem regulation is more complex than the dichotomy "top–down and bottom–up" would suggest. A common feature of many collapses in fish stocks is the combination of top–down and bottom–up effects caused by continued heavy fishing and of a series of recruitment failures caused by adverse environmental conditions (Larkin 1996). Whether the recent ecosystem changes are reversible is an open question. Other factors, both intrinsic and extrinsic, are generally associated with the ecosystem changes. Moreover, physical environmental changes may have contributed to the restructuring of the food web. At present, detecting ecosystem change is focussed on choosing some species or characteristics as indicators. Most sensitive indicators of ecosystem change are characteristics such as species diversity, the number of trophic links in a food web, the proportion of opportunistic species with high rates of increase and changes in the average size and life span of species.

5.0 HUMAN SYSTEM

Assessing and managing impacts on the biological and physical components of the Gulf of St. Lawrence requires a clear understanding of the human system. These include the governance structures, human settlement patterns and human activities occurring within both coastal and marine environments.

5.1 GOVERNANCE STRUCTURES

The Gulf of St. Lawrence is a complex multi–jurisdictional setting made up of the Government of Canada, five provincial governments (NL, NS, NB, PEI and QC), and numerous municipal governments. Federal oceans responsibilities within the Gulf of St. Lawrence include regional delegations throughout many federal departments, including Fisheries and Oceans Canada

(Newfoundland and Labrador, Gulf and Québec Regions) and Environment Canada (Atlantic and Québec Regions). First Nations and other aboriginal groups (Mi'kmaq–21, Montagnais (Innu)–7, Malecite–1 and Métis–1) share a common interest in the management of coastal and marine activities and resources. The Constitution Act (1982) and the Oceans Act (1997) respect historical treaties and traditional rights of First Nations and other aboriginal groups, recognizing their traditional ecological knowledge as an important component in understanding marine ecosystems. Thirty federal acts and more than one hundred provincial acts provide for the regulation of ocean–related activities and issues throughout the Gulf of St. Lawrence. These regulations are not necessarily coordinated among federal agencies or the five coastal provinces. At the municipal level, bylaws and zoning regulations govern coastal activities of more than 400 communities bordering the Gulf of St. Lawrence. Municipal governments have the potential to contribute substantially to the management of coastal and marine areas through responsible coastal and infrastructure planning. Non–government agencies such as industry associations, environmental and stewardship groups, and economic development boards as well as individual ocean users also contribute to the sustainability of ocean resources in the Gulf through corporate and ethical use policies.

5.2 HUMAN SETTLEMENT AND SOCIO–ECONOMIC PROFILE

Accessibility to a highly productive marine environment and markets in both inland North America and in Europe have influenced human settlement and socio–economic development around the Gulf of St. Lawrence for centuries. Based on the 2001 census, the total population around the Gulf of St. Lawrence was approximately 860,000, a decrease of about 4% from the 1996 census, perhaps reflecting some movement out of the area in recent years. The average population density in 2001 was three times the Canadian average, at 9.9 inhabitants/ sq km, with 17% of the population under age 15 and 19% over age 60, similar to the national average. Aboriginal populations showed a slightly different trend with 30–40% of the population below age 15 and less than 8% over age 60. Approximately 43% of the population spoke only English (NL, NS, NB, PEI), 51% only French (mainly Québec), 5% both English and French (NB and QC) and 1% another language. Montagnais (Innu) generally speak their own language, often in combination with French or English. In 2001, traditionally seasonal, resource–based industries (fisheries, agriculture, forestry and mining) employed 11% of the active workforce, almost twice the national average. Annual incomes averaged $23,000, with 47% of the population earning less than $15,000, both about 22% less than the national average. Meanwhile, 19% of the population had less than a grade nine education, and only 10% had obtained a university degree, compared to the national averages of 11% and of 17% respectively. This may be reflective of lower access to higher education in rural areas but there may be other factors as well.

5.3 HUMAN ACTIVITIES

Activities such as commercial fishing, aquaculture, oil and gas exploration, marine transportation, coastal and marine tourism and recreation, dredging, and a number of land–based industries have a major social and economic importance for people living around the Gulf of St. Lawrence. Industrial and economic development can place pressure on biological and physical ecosystem components and has the potential for conflict among users of ocean space.

Commercial fisheries, including ground fish, pelagic and shellfish fisheries, and marine plant and seal harvesting, target more than 50 species within the Gulf of St. Lawrence. Moratoria placed on

Atlantic salmon, Atlantic cod and redfish stocks during the early 1990s resulted in increased effort on a number of previously underutilized but potentially more valuable species, including snow crab, shrimp and lobster. Recent statistics (1997–2001) show that average landings decreased by 32% (to 223,069 t) compared to 1990–1991 (immediately prior to any moratoria on commercial fishing), while the average value increased by 37% (to $467 million) over the same period. On average, from 1992 to 2001, harp seal landings within the Gulf of St. Lawrence represented aproximatly 30% of total Northwest Atlantic seal landings. Previous fishing practices (mainly bottom trawling) have been cited as contributing to the loss of marine habitat and depletion of a number of fish stocks. Many are concerned that current fishing practices may continue to have an adverse effect on the recovery of these stocks and further result in the collapse of other fish stocks.

Approximately 1800 aquaculture sites exist throughout the Gulf of St. Lawrence, with 96% concentrated along the coast of Prince Edward Island, Nova Scotia and New Brunswick. Oyster and blue mussel production account for 99% of sites and these have experienced a 17% production growth from 2000 to 2001 (33,900 t). Ocean user conflicts, escapement of foreign and potentially invasive species, and spread of disease to wild fish stocks are areas of concern for this industry.

Oil and gas activity within the Gulf of St. Lawrence is mainly exploratory, with 60,000 km of offshore seismic data acquired since the 1960s and offshore drilling limited to less than a dozen wells (none have reached production). Meanwhile, more recent onshore drilling has produced minor discoveries on the Port aux Port Peninsula (Newfoundland and Labrador), Gaspé Peninsula (Québec) and in southern New Brunswick, where exploitation/ production licenses currently exist. Active exploratory licenses/permits exist within the offshore area of Newfoundland and Labrador, Nova Scotia and Québec, and coastal onshore areas of all five provinces. Offshore seismic operations have the potential to conflict with fishing gear and other activities. Meanwhile, little is known regarding the effect on the behaviour of marine organisms. Accumulation of drilling debris and potential spills from future exploratory and production drilling are among the environmental concerns to be addressed as the industry develops.

The Gulf of St. Lawrence accommodates approximately 6400 commercial vessel transits annually through Cabot Strait (the Strait of Belle Isle provides an alternate route during ice–free seasons), supporting domestic and international trade through the shipment of petroleum; mining; forestry, fishery and agricultural products; and cruise ship activity. While much of this traffic continues on to the Great Lakes, more than 40 ports accommodate vessel traffic throughout the Gulf of St. Lawrence. Additionally, many small ports exist throughout the Gulf of St. Lawrence, accommodating commercial fishing and recreational vessels that operate within coastal waters.

Coastal and marine tourism and recreation is an industry experiencing growth throughout the Gulf of St. Lawrence, influenced by increases in cruise ship activity, offshore excursions (whale watching and marine tours), and recreational boating as well as golf course and cottage development. A number of conservation and protected areas exist throughout the Gulf of St. Lawrence, including national parks (7) and historic sites (7), provincial parks (59), migratory bird sanctuaries (20), national wildlife areas (13) and ecological reserves (8). Many of these areas are becoming focal points of a growing tourism industry. Cruise ships and other large vessels have the potential to introduce non–native species and contaminate marine areas through bilge, ballast and wastewater disposal. Modern cruise ships accommodating more than 4,000

people per voyage (larger population than most coastal municipalities along the Gulf of St. Lawrence) are estimated to produce 400,000 gallons of wastewater per day. Coastline degradation, along with contamination of marine areas, are concerns associated with coastline development for recreational activities.

Dredging occurs within many ports and harbors throughout the Gulf of St. Lawrence to ensure the safe movement of marine vessel traffic. Annual re–dredging is required at many locations due to natural processes of erosion and sedimentation that constantly fill in marine basins. Dredging and marine disposal of dredging material activities may have some impacts on the loss of habitat and local species abundance and dispersion.

Land–based activities, particularly those that take place along the coastline, have the potential to impact the marine habitat. Approximately 21 pulp and paper mills, 13 mineral processing operations (including six aluminum processing plants along Québec's Lower north shore), and more than 200 fish processing plants exist along the Gulf of St. Lawrence. More than 1,000 dams exist on waterways that flow into the Gulf of St. Lawrence. Approximately 1.5 million hectares of agricultural land border the Gulf of St. Lawrence, with Prince Edward Island (522,964 ha), the north shore of Nova Scotia (198,008 ha) and the Bas–Saint–Laurent area (350,251 ha) of Québec accounting for over two thirds of the total acreage. Meanwhile, many municipalities still release untreated sewage into the Gulf of St. Lawrence. Land–based activities have the potential to impact marine areas through the release of biological and chemical contaminants from industrial processing, food processing and agricultural operations, and through municipal sewage and storm sewer systems. The alteration of waterways flowing into the Gulf of St. Lawrence also has an impact on migrating diadromous fish species and estuarine environments.

6.0 HUMAN IMPACTS: STRESSORS RESULTING FROM HUMAN ACTIVITIES

The major issues to be addressed at the ecosystem level are based on the current knowledge of major human activities and their related environmental stressors in the Estuary and Gulf of St. Lawrence marine ecosystem, and their significance at the ecosystem level, i.e., their implications for ecosystem integrity, structure and functioning. These issues need to focus on common stressors/pressures when resulting from multiple human activities or on specific human activities when their related stressors are unique or not similar to others (Table 1). Issues dealing with habitat destruction, parasites and diseases, waste/sewage and dredging /disposal at sea were considered to be more relevant to the regional and/or local scale. It was then decided that localized impacts with no evident significant cumulative effects at the ecosystem level would not be addressed here. Based on these criteria, seven major impact issues were identified: disturbance, impacts of the fishery activities, invasive species, climate change, freshwater inputs, chemical contamination, and coastal eutrophication.

6.1 DISTURBANCE

6.1.1 Disturbance resulting from seismic and exploratory drilling activity related to the oil and gas industry

Oil and gas development in the Gulf of St. Lawrence is in the exploration stages, primarily involving seismic surveys, and is currently small in scale but has the potential to become a major activity. However, seismic activity for exploration and research has taken place for well over 30 years and thousands of kilometres have been covered. In most cases, the methods historically

used were far more intrusive than those currently being used and frequently included the use of explosives. Explosives, which are no longer used, were known to cause immediate and massive mortality in many organisms. However, very few if any studies were conducted at the time of these surveys to document effects on the biota. A number of exploratory wells have also been drilled in the Gulf of St. Lawrence.

The effects of seismic exploration on marine animals could be significant, but there is very little information on the effects and their duration in shallow water, which is typical of the Gulf. Seismic surveys are usually undertaken over broad areas of a marine ecosystem and can involve either 2–D seismic equipment or 3–D seismic equipment. Surveys using 3–D seismic activity have line spacings much closer together, but despite the use of multiple hydrophone cables, they require longer periods of time with many more firings of airguns. The potential for impacts from seismic exploration and the cumulative effects from seismic and other noise sources may have a greater spatial impact than some other oil and gas activities. Exploratory wells and potential production facilities directly impact the marine environment locally, usually within 500 metres of the wellhead. However, there is growing concern from observations in the North Sea that contaminants in produced water, which increases in volume with age of the project, may be having impacts on the growth and reproduction of some fish species.

Seismic activities in the marine environment require the emission of sound waves in the water. Air–guns release a volume of compressed gas rapidly into the water. This action creates a bubble which expands quickly and in the process emits an impulsive signal (the primary pulse). This pulse subsequently oscillates with decaying amplitude, creating a signal called the bubble pulse. An airgun signal is omni–directional and can produce high acoustic source levels at the bubble pulse frequency (approximately 20 Hz), and at its harmonics up to at least 500 Hz (Verbeek and McGee 1995).

Depending on its intensity and frequency, sound can interfere with the behaviour of certain species and in some cases lead to physical damage. Impacts on marine animals are generally not well known, often unidentified, and likely to vary according to environmental conditions (e.g., ice coverage, bottom topography, sea conditions) and to the species exposed (behavioural activities and individual conditions).

The potential effects of seismic activities on marine animals in the Estuary and Gulf of St. Lawrence are of concern. The St. Lawrence ecosystem hosts several species having a special concern status. Therefore, seismic activities in these waters could become an additional stress factor for these species, limiting population recovery.

Precise information on the impacts of seismic activities on marine fauna in the Estuary and Gulf of St. Lawrence is extremely rare because there are very few directly relevant studies. In addition, few species have been studied, and those studies available are mostly from controlled laboratory conditions so their relevance to the field situation is unknown. With all of these uncertainties, precise impact assessment is difficult to do.

Seismic sounds in the marine environment are neither completely without consequences nor are they certain to result in serious and irreversible harm to the environment. Effects on fishing success have been noted in a few studies (Engas et al. 1996), indicating a potential for the temporary displacement of at least some fish populations, but there is no evidence to suggest that seismic surveys are of any greater or lesser importance in scaring fish than, for instance, noise associated with major shipping lanes or even some fishing activities. Scaring fish may result in

some temporary displacement, but of equal or greater importance are questions about the potential for seismic activity to actually cause biological harm. Adults, juveniles and fish eggs may suffer immediate mortality within a few metres of a sound source. In addition to immediate mortality, serious physiological and anatomical damage may also occur in the field, leading to effects such as delayed mortality, increased susceptibility to disease and predation, or impairment of egg quality.

A major factor in assessing impacts on marine organisms is a virtual lack of data on exposure–response relationships for harmful or potentially harmful effects. A recent pilot study with snow crab (Christian et al. 2004) noted few effects but drew attention to the value of establishing exposure relationships for effects on eggs since delayed egg development was noted in eggs that had been exposed to relatively high levels of sound three months earlier. Anatomical damage to the ears has also been reported to occur in fish exposed to seismic energy (McCauley et al. 1998). Such studies illustrate the need to explore the physiological and pathological effects of different sound energies on selected species at different stages of development. It would also be premature at this time to adopt specific reference levels for fish without some knowledge of the potential size of injury zones (e.g., injury/energy relationships) for fish during seismic surveys.

When assessing the effects of noise produced by a seismic airgun array on marine mammals, the level of ambient noise will influence an animal's perception of the seismic noise (Lawson and McQuinn 2004). The distances at which a given sound is audible to a marine mammal receiver and to which the mammal may react will be shorter in areas where ambient noise is relatively higher. The Gulf of St. Lawrence is a zone of relatively abundant shipping traffic. It is estimated that over 2,000 large commercial ships (tankers and cargo vessels) travel through the Gulf of St. Lawrence per year, the vast majority of these passing through the St. Lawrence Estuary to Montreal, the remainder traveling along the north shore[17]. This traffic contributes significantly to the high background noise within the Gulf of St. Lawrence (Zakarauskas et al. 1990, Desharnais and Collison 2001). Local shipping has the dominant impact in shallow waters, raising the ambient noise by up to 5 dB, while the ambient noise in deeper waters is overshadowed by more distant shipping sounds. In addition, in the proximity of fishing ports and whale–watching activities, local recreational boat traffic can result in a significant increase in ambient noise. For example, at the head of the Laurentian Channel near Tadoussac, at times of peak whale–watching boat traffic, the ambient noise can be raised by 10 dB compared to low–traffic periods for the frequencies 500 and 1000 Hz (P. Scheifele, Department of animal science, University of Connecticut, USA, unpubl. data).

The effects of seismic activity on marine mammals could range from no response, to small–scale behavioural changes, to auditory effects such as temporary or permanent changes in hearing sensitivity, to non–auditory injury such as hemorrhage and direct mortality (Lawson and McQuinn 2004). To date, there is no evidence that either acute or chronic physical impacts have occurred due to seismic sound sources, although studies of sublethal effects on wild marine mammals would be difficult to conduct.

Disturbance resulting from seismic surveys on the behaviour of marine mammals is not well

---

[17] Kelly, B. 2002. Marine commercial vessel traffic activity in Canada's Atlantic region. Prepared by Geocentric Mapping Consulting.

known in all species. Documented behavioural effects on whales include avoidance of areas of seismic activities, interference with vocalization, disorientation, modification of respiratory and diving patterns, alteration of migratory patterns and attraction of individual mammals to the sound, and secondary negative effects on food sources and habitat. Other indirect effects are also of concern, e.g., increased competition for or reduced availability of food when displaced to sub–optimal habitats increase metabolic costs. Especially when we are dealing with SARA–listed species, detrimental effects suffered by one individual can translate into detrimental effects on the population. In critical situations, the reduced fitness or loss of a single individual (e.g., the northern right whale and blue whale) becomes a concern for the health and productivity of the population (Lawson and McQuinn 2004).

Mysticeti are probably the most sensitive of the marine mammals to seismic impulses because the frequencies emitted are within the same frequency range used by these animals. Seals are also sensitive to low–frequency sounds (<1 kHz) and their auditory acuity decreases at very low frequencies. Odontoceti have poorer hearing sensitivity for low frequencies; therefore, potential auditory damage from prolonged exposure to low–frequency sounds from seismic activities is probably of lesser importance (Richardson et al. 1995). The exact hearing capability of the large toothed whales (e.g., sperm whale) is unknown, but they may hear better in the lower frequencies than the smaller toothed cetaceans. If this hypothesis is true, the impact of seismic impulses on them may be similar to those of the baleen whales (McCauley 2003).

Main key stressors for seismic exploration and exploratory drilling

- Noise related to the prolonged and frequent use of airguns (note that there are many different methods of measuring this noise and it requires experts to express it properly but it is the received levels and not the source levels that are of concern;

- Accidental spills of oil (this is usually from normal vessel operation but can include frequent but small amounts spilled when hydrophone cables are ruptured;

- Vessel strike (marine mammals and reptiles).

6.1.2 Disturbance resulting from marine traffic in the St. Lawrence and Saguenay Fjord

The major source of disturbance in the St. Lawrence Estuary and Saguenay Fjord area is linked to the marine traffic, including whale–watching activities, ferries, and shipping. This kind of disturbance can lead to the modification or the interruption of certain essential activities such as resting, feeding, vocalizing, diving, and caring for young. Depending on the type, duration, and frequency of disturbance, it can have severe long–term repercussions on certain marine mammal populations.

It is believed that beluga whales of the St. Lawrence Estuary have become accustomed to certain human activities (Savaria et al. 2003). Nevertheless, some disturbance during critical periods (e.g., parturition and perinatal activities) or in certain feeding areas could have negative impacts on the animals. In fact, diving and vocal behaviours have been observed to be modified with the approach of boats (Blane and Jaakson 1994, Lesage et al. 1999). Changes in the usual movements of belugas at the mouth of the Saguenay Fjord could also be linked to intense traffic in this area (Caron and Sergeant 1988, Pippard 1985).

Rorquals are species of interest for whale–watching activities in the St. Lawrence Estuary. It was observed by Michaud and Giard (1998) that in presence of a large number of boats, fin whales

alter their diving behaviour which consequently has negative impacts on their ability to feed. A strong negative relationship was reported (although not statistically significant) between the number of boats and the duration of deep dives associated with feeding. Therefore, these behavioural changes in diving may reduce feeding efficiency. Blue whales are thought to be more sensitive to disturbance than fin whales (Savaria et al. 2003). Since the prey of blue whales (krill) can be found in great concentrations over a larger territories than those of fin whale (mostly capelin concentrated at the head of the Laurentian Channel), they might be less affected by disturbance. The precise impacts of boat proximity on whales remain unknown and are difficult to assess.

The disturbance of harbour seals could have severe repercussions on the species, depending on the location and the time of year. Animals on haul–out sites tend to enter the water when disturbed. The tolerance and reactions of seals to disturbance are variable depending on the type of human activities (e.g., motor boat, paddleboat, pedestrian) (Henry and Hammill 2001). Disturbances during critical biological periods such as parturition, lactation, and moulting (May to mid–September) could have severe negative impacts on the animals since the seals need to remain out of the water for these activities.

The frequency of the use of certain sites by seals has been shown to decrease with an increase of human activities (e.g., Île St–Barnabé in the St. Lawrence estuary) (Savaria et al. 2003). Fortunately, seal observation activities are relatively limited. They are conducted mainly on the south shore (Bic and Rivière–du–Loup areas in the St. Lawrence estuary). However, if this disturbance becomes greater at important haul–out sites, it could have a negative impact on the seal population.

6.2 IMPACTS OF THE FISHERY ACTIVITIES

Commercial fishing in the Gulf of St. Lawrence results in the removal of large amounts of biomass particularly at higher levels in the food web (see section on the marine food web dynamic for potential impact on the food chain). Fisheries are highly regulated with respect to gear type and species or groups of species, but more work is needed to determine the impacts on habitat and the ecosystem.

6.2.1 Removal of biomass (unbalancing food web structure)

The biggest impact of fisheries on populations and communities is undeniably the increase in mortality of the targeted species or those incidentally caught. Fishing activities have direct impacts on targeted populations by increasing their mortality. These impacts will vary according to the species and fishing intensity. For example, mortality caused by fisheries would have little impact on capelin in the Gulf of St. Lawrence compared to natural mortality, which is much more significant (Grégoire et al. 2003). Furthermore, the idea that slow–growing and late–maturing species are more vulnerable to the impacts of fisheries is generally accepted.

In the absence of fishing activities, having many age classes can compensate for the possible failure of a cohort (Jennings and Kaiser, 1998). On the other hand, when fisheries eliminate a large part of these age classes, one bad recruitment year can have a large impact on the population size.

Fisheries can create a selective pressure that generates adaptive responses from the stock. This pressure is due to the fact that fisheries select individuals that are bigger and faster growing.

Fishermen generally seek larger fish because of their value and fishing gear also help to target a minimum catch size. Therefore, for heavily fished species, an individual who reproduces early has a better chance of reproducing than another that reproduces late, and the latter is likely to be caught before its first spawning. When these characteristics are partly hereditary, this favours the genotypes of individuals that reproduce earlier and at a smaller size. For many stocks, it has been observed that the fish are able to reproduce at an increasingly young age and smaller size. The average size of six– and eight year–old cod has decreased since the 1980s in the Northern Gulf of St. Lawrence (Dutil et al. 1999).

In certain fisheries, size selection also results in sex selection. Snow crab in the Estuary and Gulf of St. Lawrence is a good example of this phenomenon. Because the capture of snow crab females is prohibited, the fishery only selects males. A significant change in the sex ratio could have consequences on the population if the number of males becomes too small to fertilize all the females (sperm limitation). The number of males could also limit the number of fertilized eggs per female. However, a male can fertilize several females, and the females have the ability to retain sperm in their seminal receptacle for several years. This matter is currently being studied, and there are certain indications that recruitment could indeed be affected by a change in the sex ratio in this species (Sainte–Marie et al. 2002).

Fisheries can also affect populations during reproduction by creating additional stress. Many species such as cod and capelin are actively being fished during reproduction because they gather during this period, and catch rates are thereby higher. Laboratory studies have shown that, for cod, a hierarchy develops during the reproductive period (Hutching et al. 1999). Trawling could affect this hierarchy by displacing or removing certain dominant individuals. The additional time required to rebuild the hierarchy could lead to the loss of many eggs and thus decrease recruitment. In addition, trawling is also known to cause severe benthic disturbance as well as affect many non–target species at the individual and community level.

Fisheries can influence the structure of the ecosystem by changing in different ways the existing competition and predation relationships between species–for example, by targeting certain species whose mortality is increasing and whose biomass is decreasing. However, other unexploited species that have a similar ecological niche can see their chances of survival increase (Blanchard, 2001). Fisheries can therefore affect the diversity of an ecosystem by favouring less competitive species. The decline of certain species can also cause changes to several links in the food web, this is called a trophic cascade (see the marine food web dynamic section).

In the Gulf of St. Lawrence, the only marine mammal species targeted by large–scale commercial hunting is the harp seal. Harp seals found in the Gulf (according to the season) are part of a population that is distributed as far as Greenland. The population was heavily hunted before the collapse of European markets for whitecoats, and the biomass had dropped to less than 2 million. Population abundance then increased following the drop in hunting pressure to reach estimates of more than 5 million around the mid 1990s. However, captures have increased again since 1996. In 2000, experts from the Department of Fisheries and Oceans confirmed that if Canadian catches remained at current levels, continuous increases in Greenland harvest would have a negative impact on the size of the population (DFO 2000b). In addition to the links between seals and prey species described earlier, almost no information exists on the potential impacts of seal harvesting on the Gulf's ecosystem.

In addition to the impacts on fish and invertebrate populations described above, fisheries can

impact the entire ecosystem by changing its structure and its operation (Savenkoff et al. 2007a and b). Of all the activities that have an impact on marine ecosystems, it is probably the most significant. However, it is difficult to know what ecosystem changes are the result of fisheries since they have been going on for centuries. According to Cushing (1988), cod fishing was already flourishing in the 16th century. The challenge is therefore to assess the impact of fisheries on an ecosystem without knowing its initial condition before the beginning of human activities. Moreover, the observation of serious global changes has only recently raised questions regarding the impacts of fisheries on communities as a whole rather than only on the populations being fished (Jennings and Kaiser, 1998).

6.2.2 Habitat damage or destruction and ghost fishing by lost or damaged fishing gear

Fishing gear impacts on benthic, non–target demersal, and pelagic organisms as well as on physical and biological habitats are well–documented in the scientific literature. These impacts may include short–term effects such as sediment resuspension, digging or realignment of the bottom, destruction of habitat and organisms as well as longer–term impacts resulting in altered sediment structure, benthic communities, ecosystem processes or recruitment to fisheries (Gordon et al. 2002). However, no experimental studies specific to the Gulf of St. Lawrence have been published.

The doors and trawl from bottom trawlers drag and leave a track in the sediment. Turbidity in the water column due to the dragging is increased up to 50 m and can reduce primary production if it extends into the euphotic zone. The damage done by the trawl can have long–term impacts on softer bottoms, which depend on the benthos to provide stability, or lightly armoured bottom types, which depend on a thin cobble or gravel cover for stability. Once disturbed by heavy equipment, the physical and biological stability may be gone and these areas may become more sensitive to natural disturbance than in the past. Scallop drags have teeth, which dig into the bottom and cause a cloud of turbidity behind the drag. The drags also move sand, gravel, and cobbles and often bring up into the water column considerable quantities of these materials and create wind–rows on the bottom.

Another source of impact arising from commercial fishing activities is fishing gear that is abandoned for safety reasons or simply lost in bad weather (most often gillnets and occasionally shellfish traps and trawls). While lobster and crab traps may be equipped with biodegradable escape mechanisms, fishnets often continue to catch fish until they degrade or collapse under the weight of decomposing fish.

6.3 INVASIVE SPECIES

Invasive species in the context of this report are defined as those species in the marine community that are now considered native, but that were once in the near past non–native or non–indigenous. Some of these are indeed beneficial and valued commercially or ecologically. Knowledge is limited by the fact that it is only in recent decades that efforts have been made to systematically identify species considered invasive in the Gulf. Of course most, if not all, of that effort has been dedicated to identifying those species that are harmful or nuisance species. Little is known about alien or even potentially invasive species in the Gulf that are benign in their influence. For the sake of simplicity, the term "invasive species" is used in the general sense in this section to refer to all introduced species, whether alien or non–indigenous, whether a nuisance, harmful, benign or beneficial.

It should be recognized that range expansion of species is a normal and healthy aspect of ecology, community dynamics and evolution. Speciation (the emergence of new species, and hence the increase of biodiversity in the world) has been facilitated over the millennia by changes in competition, hybridization and genetic mixing that is associated with the gradual natural expansion in range of certain species. The most successful organisms over time are those that are able to adapt to new environments, and these are the species that are most often found expanding their range. Thus, by strict definition, at some stage in the history of all successful species, they have been "alien" or "non–native" in some part of their range. None of this required intervention by humans, and over the course of time ecosystems and communities adapted to these changes. It is only when humans intervene that this normal process is accelerated beyond the capacity of the ecosystem to effectively adapt. Consequences of such human–induced introductions are more often than not harmful. The results are more revolutionary than evolutionary, though given sufficient time; nature will undoubtedly once again establish a new balance.

Three factors determine whether an invasion will occur and whether that species will become truly invasive, die out or merely persist in low numbers. The first factor is the capacity of the species itself to become a successful invader. Such traits as hardiness, high productive and reproductive potential, broad ecological tolerance and, in some cases, an ability to enter some form of dormancy for long periods play a role in this determination. The second factor is the susceptibility of the receiving environment. Generally speaking, a disturbed environment presents a more receptive home to invaders than a healthy and stable environment. Disturbance is generally caused by human activity and can include physical and/or chemical disruption (e.g., eutrophication). However, it is generally manifested mostly in the form of biological instability, such as diminished biodiversity and lowered abundance, the latter of which can also be caused by excessive harvesting of native species. Disturbed habitat is also characterized by the presence of such hard structures as bivalve aquaculture facilities, navigational buoys, wharves, and breakwaters, all of which serve as prime habitat for the establishment and spread of many invasive species. The third factor, without which the others would have no effect, is the presence of a convenient vector to carry the invader from one place to another.

6.3.1 Importance of invasive species in the Gulf of St. Lawrence

Invasive alien species have been identified as a significant problem in a number of recent reports. Invasions of non–native species are now recognized as being second only to habitat destruction as a cause of global extinction[18].

Recent invaders in the southern Gulf of St. Lawrence have become serious pests. For example, in the last decade alone, PEI has received three important invaders that affect the aquaculture industry: the oyster thief, green crab (*Carcinus maenas*), and the clubbed tunicate (*Styela clava*). Research efforts lately have been concentrated on the clubbed tunicate since it is a huge problem for mussel growers in PEI. There has been a joint effort between many research groups to try and deal with this ever present threat to the mussel industry. This problem affects everyone using our waters–recreational boaters, cottage owners, commercial harvesters, aquaculturists and others.

[18] IUCN guidelines for the prevention of biodiversity loss caused by alien species. A guide to designing legal and institutional frameworks on alien invasive species.

Public awareness of marine invaders is increasing since aquaculture and fisheries are being impacted.

Apart from these very visible invaders, there is a whole group of invaders that are invisible to the naked eye. These invisible invaders may be potentially more devastating to human health and the health of marine resources. They include a number of toxic and non–toxic species of phytoplankton (e.g., *Pseudo–nitzschia fraudulenta*, *Neodenticula seminae*) and disease–causing organisms including *Haplosporidium nelsoni*–the mysterious MSX, or "multinucleated sphere unknown," a name that helps to emphasize how little is currently known about this haplosporidian protista. This protozoan is potentially capable of devastating the native oyster population and the entire oyster aquaculture industry in the region.

Climate change, navigation (including oil and gas exploration and fishing vessel movements), the deliberate movement of live fish and harvested fish for processing, and the degradation of natural habitats have all increased the prevalence and success of marine invasions and range extension. When a new organism is introduced to an ecosystem, negative and irreversible changes may result. Within the Gulf of St. Lawrence itself, these may include a change in biodiversity, loss of valued species (especially those already endangered or at risk), impacts on aquaculture and fishing landings and expenses associated with maintenance of gear, and loss of amenity values enjoyed by coastal dwellers and tourists alike. However, it should also be remembered that the Gulf is the front door to Canada and the US hinterland via shipping into the Great Lakes, and many serious invasive species have entered the Great Lakes basin causing irreparable environmental and economic disruption. The zebra mussel (*Dreisena polymorpha*) is only one example. Ships have brought such species as the clubbed tunicate, among others, to the Gulf of St. Lawrence. This one species is costing the aquaculture industry in PEI millions of dollars a year in extra labour and lost productivity due to the fouling of mussel culture operations in particular.

Green crab is believed to have simply made its own way into the Gulf after years of slowly progressing northward along the coast of the US from its original point of invasion, facilitated by warmer–than–normal water temperatures that allowed it to leapfrog into the Gulf over less hospitable conditions along the Atlantic coast of Nova Scotia. Since arriving in the Gulf in 1995, it has benefited from warmer winters and effluent–warmed estuaries to build up its numbers.

Many species that we now consider endemic in the Gulf were in fact alien invaders of earlier eras before careful record keeping on species distribution existed. Sea lettuce (*Ulva lactuca*), for example, may or may not be an endemic species in the Gulf. Regardless, it would likely not be a problem if nutrient loading in the areas where it now proliferates had been kept low.

If habitats are healthy and not stressed, native species might normally be able to out–compete at least some of these invaders, since they are best adapted to their local niche. But harmful invasive species take full advantage of the new degraded or changing niches to become established. Also, some introduced species fill empty niches or ones left partially occupied due to over–harvesting of endemic species and can thus change the food web dynamics. Strenuous efforts are needed to prevent introduction from ballast water and by the other common vectors mentioned above.

No scientist can be sure which of the better–known species in the Gulf today were there from the earliest days, long before the advent of humans. There are 21 species that can be stated with certainty to be invasive in the southern Gulf and eight more in the northern Gulf. No explanation

has been found for this geographic dichotomy. Suffice it say that the majority of new invaders appear in the warmer, shallow areas surrounding Prince Edward Island or Northumberland Strait between PEI, Nova Scotia and New Brunswick. This area may be more hospitable to their initial survival, after which they seem to move out from there. There have been reports of at least some secondary invasions of species that were accidentally introduced into the Great Lakes system in ballast water and then made their way back to the St. Lawrence River and estuary, but this far less common.

In recent years, green crabs have been positively identified in the Îles–de–la–Madeleine (Paille et al. 2006). It is a major but not unanticipated jump in its previous distribution. Recently, a few specimens of the Chinese mitten crab (*Erocheir sinensis*) were caught in the upper portion of the St. Lawrence Estuary (Y. de Lafontaine, Centre Saint-Laurent, Montréal, QC, personnal communication). This crab is generally considered as one of the 100 most pervasive species in the world. The highly invasive skeleton shrimp *Caprella mutica* is present at all mussel farms near Carleton in the Baie–des–Chaleurs (B. Sainte–Marie, Maurice-Lamontagne Institut, Mont-Joli, QC, personnal communication). In addition, a native but non–indigenous species has recently arrived in the Gulf: the large predatory arctic hyperid amphipod, *Themisto libellula*, has successfully colonized the northern Gulf of St. Lawrence (ca. 1993) and the southern Gulf of St. Lawrence (ca. 2000). It is now a permanent part of the midshore community (Harvey et al. 2003). Finally, juvenile (age–0) blue crab (*Callinectes sapidus*), a native of US waters from Massachusetts south, have been sighted in small numbers in the Gulf, but it appears that they are not able to survive the winter. Some Canadian scientists believe it is not too extreme to declare that an ecological meltdown is underway in the southern Gulf as a result of the rampant spread of these exotics.

6.3.2 Potential introduction and range extension of invasive species

From marine transportation

Most authorities agree that the single most important vector of marine invasions today is the ballast water of large ocean–going vessels. This explains why the pace of invasions has accelerated so dramatically in recent decades. Modern vessels travel with ballast when insufficiently loaded with cargo, and the ballast used today is generally composed of seawater taken on board at whatever port that vessel has last visited.

There are two known vectors of marine transport of alien species: in ballast water and hitchhiking as hull–fouling organisms. Ballast water is almost certainly the more serious of the two for long–distance movements, while hull fouling (along with fouling of fishing gear, boat trailers, etc.) is considered the prime vector for dispersal once an invasion has taken place.

Ballast water has been associated with the unintentional introduction of a number of organisms in Canadian waters and several have been extremely harmful to both the ecosystem and the economic well–being of the coastal and riparian community in Atlantic Canada and the Great Lakes. Transport Canada has established guidelines intended to minimize the probability of future introductions of harmful aquatic organisms and pathogens from ships' ballast water while protecting the safety of ships.

Many of the species that can be brought in ballast water can also travel on ship hulls. In addition, there are other organisms that are virtually excluded from ballast water intakes on well–managed ships that can quite easily attach themselves to hulls for relatively long journeys while lying

dormant. This was the method of transport for invasive species prior to the use of water as ballast and continues to be the most prevalent method of invasive species dispersal within the Gulf after an initial invasion has taken place. Little is being done to address this vector.

Other primary and secondary pathways of invasion, known or suspected, include the movement of live fish and shellfish for aquaculture or processing, the movement of raw fish (in salt water or seaweed packing) for processing, the use of live bait captured or purchased outside of the Gulf, and possibly the release (usually deliberate though not malicious) of fish no longer wanted by aquarium owners. All of these require more careful study to determine the risk they pose, if any.

From commercial fishing

There can be little doubt that the constant movement of fishing vessels from home port to fishing grounds to processing plant has been and continues to be a constant vector for the dispersal of invasive species, once they have been introduced into the Gulf of St. Lawrence from elsewhere in the world. The mechanisms involved are hull–fouling and movement on fishing gear. Fishing vessels used in the Gulf do not carry ballast water, by and large, though there is a constant exchange of bilge water, especially in stormy conditions. Even this minimal exchange is sufficient to assist the gradual movement of planktonic and small particle propagules leading to significant range expansion of various species of invasive organisms over a long period of time.

Lobster and crab fishing represent quite different activities in terms of their potential to act as vectors of invasive species dispersal. Lobster fisheries in the Gulf are local fisheries, carried out within a short distance of the homeport. Crab fishing is carried out in deeper water and sometimes at great distances from the home port. Furthermore, crab fishers tend to search out the best price available before landing their catch and, because of the large size and speed of their vessels; they are quite capable of taking that catch to any port within the Gulf to get that price. Therefore the potential for carrying an existing invasive species further within the Gulf is considerably greater in the crab fishery than in the lobster fishery. However, the types of invasive organisms that are causing the most devastation in the Gulf at this time are fouling organisms like the clubbed tunicate which frequent shallow waters and are therefore more likely to attach themselves to lobster traps than crab traps.

From land–based activities

There are two possible land–based vectors of marine invasive species that have not been adequately explored. The first is the risk posed by the increasing movement of live fish for the aquarium trade. While most of these species are tropical and unlikely to be able to survive in the harsher environmental conditions of the Gulf, it is known that this vector has contributed to invasions elsewhere in the world and it may only be a matter of time before the same occurs in the Gulf of St. Lawrence. Secondly, unprocessed fish for primary and secondary processing in seafood plants in the Gulf is being imported from other parts of Canada, the US and farther afield at a rapidly increasing rate. The risk of invasive species hitching a ride in water or packing materials accompanying these imports is a real but unquantified concern. A considerable potential source of invasive species is the transfer of lobsters to and from the United States to all regions of the Gulf of St. Lawrence, which is exempt from the regulations outlined in Canada's Introductions and Transfer Policy (this policy covers concerns about invasive species on the lobster and in shipping material and holding containers).

From aquaculture

Canada has stringent controls on introductions and transfers, primarily set in place to prevent disease dissemination among the species being cultured. These mechanisms do restrict the movement of pathogens and also can restrict movements of inadvertent hitchhikers. Great care is being taken to avoid inadvertent transfers of species, but improvements are still required.

To date a number of invasive species have been introduced in the region, either by the aquaculturist or via other vectors, and they have had a major impact on the shellfish aquaculture industry. An early example is the propagation of the Malpeque disease caused by the introduction around 1910 of oysters from the United States for research purposes (Medcof 1968). More recent examples include the green crab, oyster thief and clubbed tunicate in PEI and the protozoan, better known as MSX (for "multinucleated sphere X [unknown]"), in the Bras d'Or Lakes of Cape Breton. Care has to be taken to avoid transfers of species, which could escape and harm the ecosystem.

6.4 CLIMATE CHANGE

In recent geologic time (approximately 10–20,000 years ago), the Gulf of St. Lawrence would have been unrecognizable to us. The area was fully or partially covered with permanent ice fields. The geologic process and global dynamics associated with an overall trend of global warming and the associated action of glacial retreat and ice melt helped form the present–day ecosystem. The shift from an ice–covered ecosystem to the present–day temperate ecosystem (boreal–temperate species boundary) was a natural process that occurred over time scales of centuries to millennia. This gradual global process is a geologic oscillation between glacial and inter–glacial periods. The salient point is that an ecosystem is always in a continuous cycle of change influenced by natural variables. However, there is increasing evidence of a human–induced macro–scale effect on global climates due to increased loadings of carbon dioxide, methane, nitrous oxides, chlorofluorocarbons and other greenhouse gas emissions from human sources. The influence of human activities on this oscillation and other processes and cycles of ecosystem change are now considered to have a perceptible impact on climate change.

In a changing climate, the timing and amount of precipitation, warmer temperatures, higher evaporation, less water availability, and extreme events will all affect natural ecosystems. However, as with all stressors, it is expected that natural ecosystem responses to a changing climate are likely to be non–linear; change may not occur until a threshold has been reached and then rapid, dramatic transitions may occur. Ecological surprises are expected. Some species will benefit while others will not. Detailed assessments of impacts on particular species and ecosystem functioning are limited by our lack of understanding of the complexity and interconnectedness of ecosystems (Fisher et al. 2000).

However, biological productivity is expected to increase with moderate temperature increases. Species distributions will change, with more southern species moving into the Gulf of St. Lawrence. Introduction of invasive species could be accelerated. Species currently in New England could move north. Existing community structures and interactions may change. A changing climate is expected to lead to reduction in some habitats. Wetland vegetation communities, functioning, and values will change as the marshes and lagoons fail to adapt to the increasing rate of rising levels, and rare and endangered species may be more vulnerable.

6.4.1 Potential effects of climate change

On invasive species

Changing habitat conditions, including warmer water, reduced sea ice, eroding coastlines, and changing currents, will create conditions suitable for species from the south to move into the Gulf of St. Lawrence. Invasive species have been restricted by the cold winters, but the warming temperatures will permit them to become established. Species that prefer cold water will move out of this area, and expected increases in the inflow of colder, lower salinity flow of water from Labrador will keep these species along the north coast and western Newfoundland. The current invasion of green crab in the Gulf took place, as far as can be determined, through a slow and progressive movement up the coast of North America from the site of its first introduction decades ago. Its further dissemination throughout the Gulf is almost guaranteed now that it is present in large numbers in certain locations. This sort of movement, assisted by the generally warmer conditions along the coast due to climate change, will undoubtedly increase and accelerate in the future. Our endemic species are the potential alien invasive species of distant ecosystems, and efforts must therefore be made to prevent their dissemination via the same mechanisms that have caused so much difficulty in the Gulf of St. Lawrence.

On currents and water temperature

As the seawater warms globally, sea level rises due to the melting of ice caps in the polar regions but primarily to the expansion of the water itself. In the Gulf of St. Lawrence, water temperatures in the deep water may lower due to a stronger Labrador Current, but the longer warmer summers will heat the surface water, setting up stronger stratification and less mixing, which will lower the over–all productivity. PEI and the Îles–de–la–Madeleine are considered the second most sensitive places in Canada to the effects of sea level rise.

The earth is heating up due to the increasing use of fossil fuels. The furnace oil we heat our homes with, the gasoline we fuel our cars with, the diesel fuel used to grow and transport food products and a host of other energy–based services are contributing to what is called Global Warming. Burning fossil fuels like furnace oil and gasoline produces carbon dioxide and other gases which, when released into the earth's upper atmosphere, create a greenhouse effect that traps heat within the earth's atmosphere.

On salinity

Most climate models agree that in the Great Lakes watershed and the Gulf of St. Lawrence there will be an effect on the magnitude of the mean, minimum, and extreme freshwater flows as well as a change in their seasonal distribution and duration. Annual outflow decreases are expected despite precipitation increases. These changes in river flow will affect the estuarine circulation in all coastal areas as well as the Gulf of St. Lawrence in general. This could have a profound affect on species that depend on a combination of water temperatures and spring phytoplankton blooms initiated by spring freshets.

On flow variability

The largest part of the volume of freshwater that supplies the estuaries and ultimately the Estuary and Gulf of St. Lawrence ecosystem comes from the basins that drain in them. The quantity of

water that reaches the estuary is the difference between precipitation and evaporation. Consequently, climate change will probably become one of the major sources of flow variation in the decades to come.

The last report from the Intergovernmental Panel on Climate Change (IPCC) projected an average global temperature increase of between 1.4 and 5.8°C for the beginning of the next century (Intergovernmental panel on climate change 2001). Temperature increases are usually met by significant seasonal variations in precipitation variations. For every increase of one degree Celsius globally, a 4% increase in precipitation can be expected, and North America is very sensitive to these variations (Labat et al. 2004). In natural settings, this could translate into an earlier spring freshet or even heavy rainfalls in the middle of the winter for areas further south. Although it is difficult to calculate the changes, models predict an increase in precipitation on all the Great Lakes drainage basins and the Gulf of St. Lawrence. Summers will be dryer while winters will experience a significant increase in precipitation (IPCC 2001).

6.5 FRESHWATER INPUTS

Freshwater inputs in the St. Lawrence River system (Estuary and Gulf) are mainly provided by the numerous tributaries of this river watershed (1.5 x 106 km2). Mean annual flows at Sorel represent 9,868 m^3s^{-1} of freshwater entering the estuarine system towards the Atlantic Ocean. The major tributaries of this watershed are regulated using different works designed for hydroelectricity generation, flooding control, and irrigation as well as for recreational or industrial use. Rivers not yet regulated are mostly located in the periphery of the Gulf. The increasing outflow from large Arctic rivers (ACIA 2005) and the melting of the Greenland icecap (Johannessen et al. 2005, Zwally et al. 2005, Rignot and Kanagaratnam 2006) are other sources of freshwater that feed the Labrador Current and enter the northern Gulf of St. Lawrence, mainly through the Strait of Belle Isle. Long–term trends for near–surface temperature over the last decade showed a freshening pattern that extends to the entire Gulf (Drinkwater and Gilbert 2004).

In the context of marine productivity, runoff water is often considered only as freshwater entering sea water, with all the physical mixing mechanisms and associated currents. However, freshwater is also a vehicle for a wide range of chemical compounds of natural or anthropogenic origin. Hence, lithologic proprieties of the watershed, biological production, land use (agriculture, flooding, recreational, etc.) and waste waster from human and industrial origins are all affecting the quality of the freshwater that enters the estuarine and coastal systems. The amount of precipitation and the decisions made regarding reservoir management will dictate the timing and volume of freshwater that actually enters the Gulf of St. Lawrence.

When concentrating on how the Gulf of St. Lawrence functions, one focuses immediately on the size and flow of the St. Lawrence River. While the two systems are considered as unique and continuous, the mechanisms responsible for productivity in the Estuary appear to be very different from those found in the Gulf, starting with the timing of spring blooms. The multitude of rivers, such as the Saguenay, Manicouagan, and Miramichi rivers, to mention only the larger ones that drain into the Gulf of St. Lawrence, makes the Gulf dynamics very complex. However, it would not be surprising if some of the processes occurring in the estuaries of these smaller rivers could have an equally significant impact on our understanding of the Gulf as a whole and of its functions.

6.5.1 Impacts of freshwater runoff on estuarine, coastal and marine ecosystems

Trying to understand the impacts of freshwater runoff variability on ecosystems like the Estuary and Gulf of St. Lawrence can be very challenging (Ardisson and Bourget 1997). The many variables involved can act and interact in different way, at different spatial and time scales. Furthermore, the volume of water entering the estuarine system can vary naturally on an hourly, weekly, seasonal and interannual basis, or anthropogenically due to water management decisions. Each of these scenarios has the potential to trigger a different response from the ecosystem.

The general physical, biogeochemical and biological processes occurring in the St. Lawrence Estuary are generally well known (El–Sabh and Silverberg 1990, Therriault et al. 1990). The variability of freshwater input causes changes in the physicochemical properties of water masses, which help stabilize surface water masses, flow and current velocity, nutrient availability and sediment load (Figure 5). The phytoplanktonic bloom onset is essentially controlled by the mixed layer depth, the water column stability and the amount of light (Levasseur et al. 1984, Therriault and Levasseur 1985, Savenkoff et al. 1997). Although the massive influx of freshwater initially generates a heavy stratification of the water column, it is only when runoff slows down and jet stream velocity decreases that the spring bloom begins. The time spent in the Estuary must be long enough to allow for the accumulation of phytoplanktonic cells. Besides explaining the role the spring freshet has on the spring bloom, this also highlights the role of interannual variability (Zakardjian et al. 2000). These variations also have an immediate impact on currents and larval dispersion as well as community make–up.

Turbidity is often ignored in freshwater systems even though it plays a significant role in productivity at several levels. Cloudier is water, the more it contains suspension mater. Most nutrients usually come from sediments, at least in the coastal area. It is also the key factor in limiting light penetration, with all the related impacts on primary production. Turbidity will also modify habitat quality by changing the formation and granulometry of deltas.

Contaminants are generally carried by sediments bound with minerals and/or organic matter. Lebeuf et al. (1999) showed that, although occurring at concentrations well below the Canadian guidelines for the protection of human health, PCBs and organochlorine pesticides accumulate in Atlantic cod, American plaice and Greenland halibut found in the Northern Gulf.

Light penetration is a significant variable for photosynthesis and, consequently, for blooms. River outflows carry a sediment load that enriches surface waters with nutrients but also alters the amount of light penetrating the water column. Since most top predators rely on their vision to feed, the absence of light and the lack of visibility has a significant effect on feeding (Drolet et al. 1991, Gilbert et al. 1992), even when food is abundant. However, high turbidity areas may also provide cover against predation, which compensates the energy drop and sustains growth (Sirois and Dodson 2000).

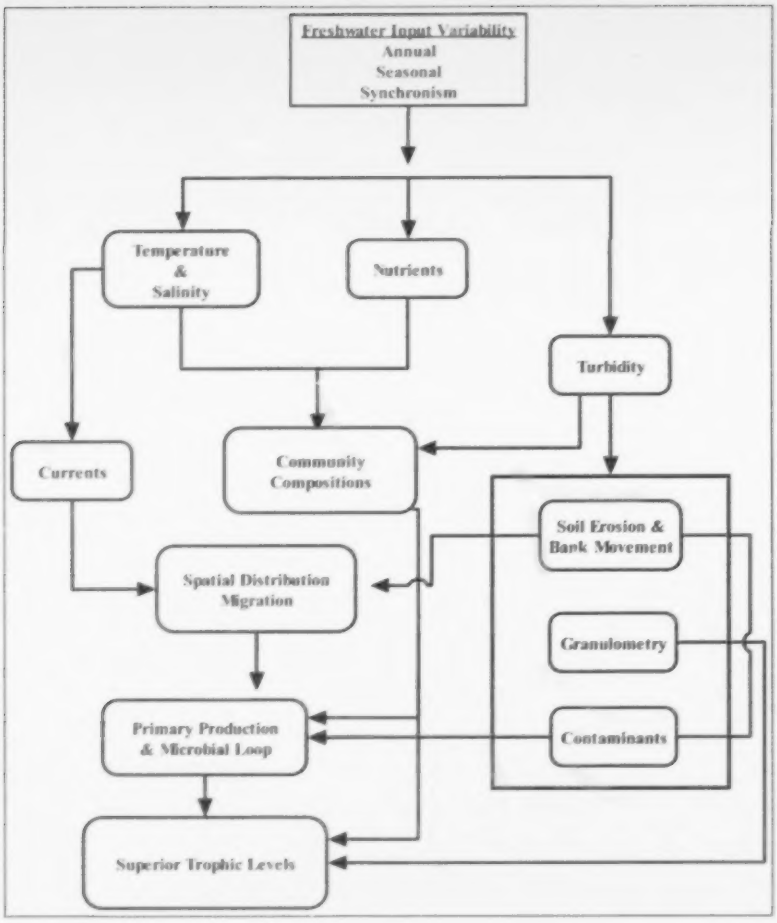

Figure 5. Pathways of impacts of freshwater influx on marine production

6.5.2 Impacts on biodiversity

Under selective pressures, the environment's biophysical and biochemical structure can stimulate the production of organisms that otherwise remain in low abundance. Weise et al. (2002) showed that the variability of freshwater runoff from only one river could trigger the onset of a toxic algal bloom. The stabilization of the water column, combined with light wind events, allowed these organisms to develop and spread over a significant area in the Gulf.

The dispersion of larval stages is often critical for recruitment and for sustaining marine populations. The dynamics of large calanoid copepods in the St. Lawrence Estuary is greatly influenced by the estuarine circulation (Plourde et al. 2001, 2003), the timing between the end of diapause and emergence in surface layers with the spring bloom being critical for the development of these populations. Also, the dispersion of both benthic and pelagic organisms in Arctic seas is greatly influenced by variations in river flows (Fetzer and Deubel 2006). The path of a river plume varies according to flow changes, carrying larvae towards substrates that could be inappropriate, for example, for the survival of benthic larvae.

6.5.3 Links with fish stocks

It is generally assumed that linkages between freshwater flows from rivers and recruitment in fisheries passed through phytoplancton developpement and it browsing by the highest trophic levels. Unfortunately, the literature offers little in terms of monitoring marine productivity variations induced by precipitation or water runoff variability associated with an increase in temperature resulting from climate change. This could perhaps be explained by the fact that temperatures are much more predictable than precipitation, freshwater outflow or wind direction. Hence runoff variability on the general physical oceanography and its cascading effects on the food web are largely unknown (Drinkwater 2005).

In the Gulf of St. Lawrence, several studies have focussed on the relationship between freshwater flows and marine species recruitment. However, in most cases, whether for crustaceans and groundfish (Sutcliffe 1973) or pelagic fish (Runge et al. 1999, Ringuette et al. 2002), the mechanisms underlying these relations are usually not understood, and tend to lose their significance in the long term. Small–scale studies tend to show better linkages between biomass production and runoff (Ardisson and Bourget 1997).

6.5.4 Impacts of river development on flow variability

In the early 1990s, the flows of 13% of the world's rivers were regulated one way or another (Milliman 1997). Altogether, 663 large reservoirs (> 0.5 km^{-3}) actually trapped more than 40% of the world river discharge. Over 50% of the sediments are thus retained (Vörösmarty et al. 2003), thus reducing nutrient and silicate loads (Humborg et al. 1997) and causing a diminution in primary production as well as a change in the phytoplanktonic community structure (Milliman 1997). Silicate limitation supports a shift from systems usually dominated by diatoms towards systems dominated by dinoflagellates, accompanied by an increased incidence of blue–green alga.

From the beginning of the twentieth century, the volume of hydroelectric reservoirs increased by 200 km3 in 1968, with the launching of the operations at the Daniel Johnson (Manic–5) dam (Bugden et al. 1982). In order to fulfill Québecers growing energy demand in the 70s, the harnessing of several rivers in the Northern Gulf of St. Lawrence watershed was planned. The impacts of these water flow regulation works have been discussed from a more or less theoretical perspective (Hassan 1975, Drapeau 1980, Bugden et al. 1982, Neu 1982a, 1982b). However, according to these studies, there is no reason to assume that large–scale freshwater modification schemes would not produce basics change in areas that could extend far beyond the boundaries of the seas. Since then, another 24 km3 of reservoir volume has been added. Moreover, on the Québec territory only, there are 5357 structures dedicated to flow regulation. Even though in terms of reservoir capacity hydroelectricity generation clearly outplayed every other structures pooled together, they represent only 14% of existing structures (Centre d'expertise hydrique du Québec; www.cehq.gouv.qc.ca/barrages/). The remaining rivers not yet harnessed all flow into the northern Gulf of St. Lawrence.

Still today, few studies fully assess the large–scale impacts of hydroelectric development and usually focus on local impacts, overlooking the coastal and marine systems, that are often located several hundred kilometres downstream of the dam itself (Rosenberg et al. 2007). This clearly demonstrates the difficulties to fully embrace all the different time and spatial scales involved in these large projects.

The huge watershed of the Great Lakes, draining a surface area of 1.5 x 106 km^2 into the Gulf of St. Lawrence, represents the main freshwater supply to the Gulf of St. Lawrence. This watershed is the most densely populated area in Canada, and the mix of heavy agricultural and industrial activities found there adds a significant amount of fertilizers and pollutants of all kinds to the freshwater (Climate Change Impacts and Adaptation 2004). The flows of almost all the rivers that flow into the Gulf of St. Lawrence are regulated, except for rivers of the Québec Lower north shore (Northeastern Gulf). This greatly limits interannual variations, as well as maximum flows, since the objective is to accumulate water for hydroelectricity generation and maintain navigation on the St. Lawrence Seaway. It is important to mention that the management of water flow patterns is not the only source of impacts, as the design (the engineering) of works also produces its own impacts (Berkes 1982).

Synchronicities with biological components of the ecosystem as expressed earlier can be jeopardized. As a direct impact, dam's structures will provide a more constant outflow throughout the year by attenuating the spring freshet in favour of winter. This pattern also leads to the alteration of the physico–chemical structure of the water flowing towards the ocean, causing a disturbance in temperatures, sediments and nutrients. The development of new market for electricity with the South will potentially bring another pulse on freshwater use during the summer (for air conditioning), thus creating ideal conditions for a toxic algae bloom (see Weise et al. 2002).

Large–scale changes resulting from climate change will have fundamental effects on the ecology of the Estuary and Gulf of St. Lawrence ecosystems. Climate change will probably modify freshwater inputs, both terms of volume and timing. It is believed that this will warm the surface layers faster and bring them to higher temperatures than before in the St. Lawrence River system, while a stronger cold Labrador Current will cool down the deep waters. The result should be longer and stronger summer stratification reducing the mixing of nutrients into the euphotic layer. Some of the weaker mixing areas could not function with a stronger stratification. The overall result should be lower productivity. However, these are suppositions, and better predictive models designed at the scale of the Gulf of St. Lawrence watershed as well assessments of the impacts are needed.

There is still much work to be done in order to have a clear understanding of the ecosystem that would then enable us to predict the evolution of the system resulting from flow changes in the estuaries or climate change. Part of the problem stems from our inability to accurately predict freshwater flow variations (Climate Change Impacts and Adaptation 2004). The absence of both physical and biological data at the level of ocean systems makes the study of causal links between freshwater influx variability and production very difficult (Royer et al. 2001). This conclusion reflects previous knowledge assessment of the Estuary and Gulf of St. Lawrence systems (Drapeau 1980, Neu 1982a, 1982b, de Lafontaine et al. 1991).

6.6 CHEMICAL CONTAMINATION

Contaminants present in the marine environment include inorganic compounds that do not contain the element carbon and hydrogen, such as metals (mercury, cadmium, lead, etc.), and a massive range of organic compounds such as organotins (TBT), organochlorines (PCBs, DDT and metabolites, mirex, toxaphene, dioxins, furans, etc.), polybrominated hydrocarbons (PBDE), polycyclic aromatic hydrocarbons (PAHs), non–persistent pesticides (carbamates, triazines, organophosphore), detergent, pharmaceutical products, and others. Many of the organic

contaminants are hydrophobic, which means that they could be absorbed on particulate matter and be taken up in the food chain. Some highly persistent organic pollutants are widespread in sediments and organisms. Metals as mercury accumulate in the biota in their organic form. Information on contaminants comes generally from sediment or biota studies instead of water and atmospheric ones.

Contaminants can have negative effects on the cells and tissues of exposed individuals, populations, and even entire communities. In fact, some contaminants taken up by an organism at the base of the food chain can travel up through trophic levels, becoming progressively more concentrated. The action of contaminants translates into physical effects; for example, metals act directly on cell membranes. Effects can also be physiological, as in the case of certain organic compounds, which have a chemical structure similar to that of hormones and can perturb the functioning of the endocrine, immune, and reproductive systems. The effects of contaminants also vary according to the species affected and on the level of contamination in the organism (the toxic load). For persistent compounds, the toxic load is generally proportional to the degree of exposure, and the organism's trophic level, and varies according to individual stage of development or physiological factors such as metabolism or sex. Some of the contaminants accumulated in females can be transferred to their eggs, embryos, or maternal milk.

Different types of toxicity are defined according to exposure. Acute toxicity, which may cause the loss of vital functions and mortality, is generally associated with a short period of exposure (from a few hours to a few days) to high concentrations of a chemical product (Ramade 1979). The acute toxicity of a wide range of toxic components is relatively easy to measure and often constitutes the only information available to evaluate the risks associated with a given environmental situation. This knowledge is useful, for example, in the case of an accidental spill. Acute exposure to sublethal concentrations of endocrine disruptive substances at a critical stage of development can lead to irreversible effects (e.g. Fairchild et al. 1999). Chronic toxicity can be defined as the sum of effects observed after medium– to long–term exposure to a contaminant. Longer term toxic effects observed are more insidious as the degradation of the general health of organisms and changes in their life cycles. This type of toxicity, which is much more common in the natural environment than acute toxicity, is difficult to detect and recognize.

Various tolerance thresholds have been proposed to establish the level of contamination or toxicity of a substance within the ecosystem (i.e., in the water column or in the sediments) as well as in living organisms (i.e., in the tissues of certain organs or in fatty tissue). Standard thresholds have also been established to determine the safety levels for human consumption. The concept of tolerance thresholds applies more hardly to the less persistent compounds but which present an uninterrupted exposure to the organisms without building up therefore in their tissues.

6.6.1 Sources, transport and distribution

The waters and sediments of the St. Lawrence contain numerous contaminants that come from a variety of sources. These sources vary according to the type of contaminant and can be localized or diffused within the system or external to it. The primary sources of contaminants in the St. Lawrence Estuary and Gulf may be their tributaries, mainly the St. Lawrence and the Saguenay Rivers. Most contaminants come mainly from the large urban and industrial zones.

The main local sources of contaminants are untreated urban, agricultural and industrial waste as well as resuspension of sediments, mainly through dredging activities. These more quantifiable and localized sources are subject to the application of environmental protection regulations.

However, there are also diffuse and unquantifiable pollutants brought into the system by atmospheric transport (in the form of gases or aerosols) and by runoff from the St. Lawrence drainage basin, which is impacted by agricultural and forestry activities.

Except for some pesticides (ex. TBT), organic persitent contaminants are generally not very soluble in water and the concentrations found in dissolved form are very low. Hydrophobic contaminants are transported in the ecosystem by suspended particulate matter onto which they can be attached by sorption[19]. As with suspended matter, sediments are their primary storage sink in the ecosystem. These processes also explain the greater concentrations of contaminants in the maximum turbidity zone (MTZ) of the Upper Estuary, the upstream section of the Lower Estuary, and in the inner basin of the Saguenay Fjord. However, proximity to urban and industrial areas influence the concentration of contaminants in the sediments of the St. Lawrence. Heavier particles are deposited close to their source while smaller particles are transported over longer distances and are deposited in places where the currents are weak. This phenomenon results in the global contamination of the Estuary and the Gulf. There are also zones such as the Laurentian Channel and others that are even more contaminated. In shallow waters, physical phenomena, such as tides, storms and ice movement, and chemical phenomena, such as precipitation, adsorption of chemical products and the degradation of molecules in the sediments, continually redistribute contaminants into the environment.

Although sediments represent a final sink of contaminants, they can also be absorbed and accumulated in benthic and other marine organisms. This process is referred to as bioaccumulation and occurs when an organism cannot metabolize all the load of an absorbed contaminant. The contaminant then accumulates in fatty tissues if it is an organic compound or in all tissues in the case of metals. However, organic compounds can accumulate in other tissues depending on their solubility and the species. These contaminants are then transferred to organisms at higher trophic levels through predation and accumulate even more in living tissue. This phenomena, called biomagnification, increases the quantity of persistent toxic molecules as they travel from lower to higher trophic levels, and explains why, in general, higher concentrations of contaminants are observed in top predators. A case in point is the belugas of the St. Lawrence, which have high levels of certain contaminants in their tissues.

6.6.2 Metals

A number of metals are normal constituents in living organisms and some are essential to biological processes such as photosynthesis and metabolism. They can, however, become toxic at high concentrations, which is why research on the quality of the aquatic environment generally pays special attention to their presence.

A large quantity of metals comes from industrial waste and urban effluents, agricultural activities, and dredging. These contaminants enter the St. Lawrence River directly from effluents and runoff and indirectly from the atmosphere. Metals present in the sediments in a bioavailable form can be bioaccumulated in the food web. Their bioavailability is essentially related to their solubility in water, which is governed by physical–chemical factors such as pH and the potential for oxidation–reduction (Eh), and the quantity of organic matter in suspension. As saline water

[19] Assimilation of molecules of one substance by a material in a different phase. Adsorption (sorption on a surface) and absorption (sorption into bulk material) are two types of sorption phenomena.

has a higher pH than freshwater, the metals in the St. Lawrence, its tributaries, and the effluents flowing into them tend to precipitate when in contact with saline water. This explains why metal concentrations are generally higher in the Estuary than in the Gulf.

The annual influx of a large number of metals into the St. Lawrence at Québec City was calculated by Cossa et al. (1997) from data collected in 1995 and 1996. Their results showed considerable input of mercury and lead, two highly toxic metals. After passing from the freshwater of the St. Lawrence River to the brackish and saline waters of the Estuary, little is known of the fate of these metals. There is virtually no data on the metals present in the waters of the Upper Estuary between Île d'Orléans and the mouth of the Saguenay. The only data available for total mercury (dissolved and particulate) present in the waters of the Lower Estuary are those of Gobeil et al. (1983). These data indicate that concentrations of mercury vary little with depth.

Concentrations of metals in the sediments of the Estuary and the Gulf are better known. Gobeil (1991) determined the metal content in the sediments of some stations situated in the Laurentian Channel, between the Lower Estuary and Cabot Strait. They revealed the presence of concentration gradients of lead, mercury, zinc, and iron (Figure 6). The higher contamination observed in the upper reaches of the Lower Estuary is explained by the proximity to a greater number of sources of metals. As mentioned previously, contaminants in general have a tendency to accumulate close to their source and concentrations decrease according to distance from that source. The phenomenon was observed on a smaller scale in Baie des Anglais, one of the best known sources of other contaminants, situated on the north shore of the Estuary (Lee et al. 1999, Smith and Schafer 1999).

Gobeil et al. (1997) analysed concentration of mercury, lead and cadmium in various tissues of fish and crustaceans taken in the Saguenay Fjord, the estuary and the northeast of the gulf of St. Lawrence. They observed the highest concentrations in the Saguenay Fjord. In other sites of the St. Lawrence river, concentrations observed in the liver, muscle tissues and gonades were weaks and below Canadian norms for human consumption (0.5 mg kg^{-1} humid weight). However, metal concentration in the liver of fish, hepatopancreas of crustaceans (Rouleau et al. 2001) and gonades of fish and crustaceans were higher than those found in muscle tissues.

In 2001, concentrations of cadmium (Cd) in whole scallop cultured on the north shore of the St. Lawrence Estuary exceeded the European guideline for protection of human health (2 g $Cd{\cdot}g^{-1}$ wet weight, now revised to 1 g $Cd{\cdot}g^{-1}$ wet weight). In 2002 to 2004, mean concentrations of Cd in whole wild scallop (*Placopecten magellanicus* and *Chlamys islandica*) collected on the North shore of the St. Lawrence Estuary were also higher than 1 g $Cd{\cdot}g^{-1}$ wet weight. Concentrations of Cd were greater in *Platopecten* then in *Chlamys* with a greater proportion of Cd accumulated in the hepatopancreas in *Platopecten*. On the north shore of the St. Lawrence Estuary, most of the cadmium is from natural source, originating from the natural rocks and transported in the rivers to the Estuary. The environmental factors promoting its accumulation in scallops and the pathways of transfer of cadmium in the food chain are under investigation (Guillemart 2006).

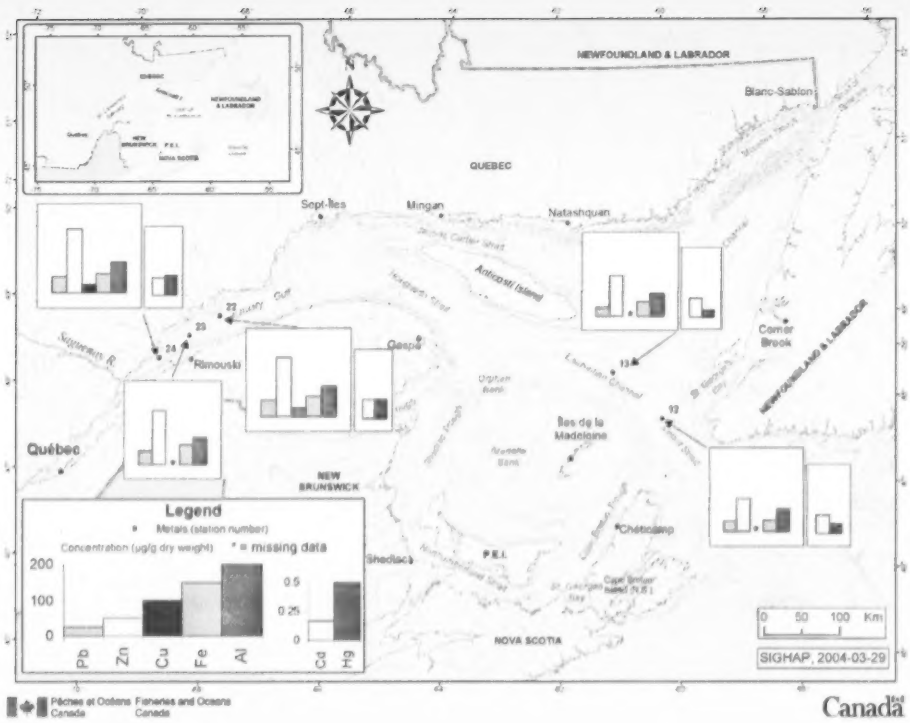

Figure 6. Concentrations of metals (µg g^{-1}) in surface sediments in the Lower Estuary (0 to 4 cm) and the Gulf of St. Lawrence (0 to 2 cm). From Gobeil (1991).

Concentrations of cadmium were recently found to be 10-20 times higher in the amphipod (*Themisto libellula*) compared to krill. Oceanographic changes have recently induced a marked increase in the biomass of *Themisto*, a cold water species, which is now more abundant than krill. The impact of these changes on exposure and risk of impacts in predators such as whales or fish are under investigation[20].

Kennedy and Benson's work (1993) on mussels along the Newfoundland coast revealed a slight metal contamination. Nevertheless, the levels observed are within Canadian standards for human consumption. Arnac and Lassus (1985) determined metal content in the liver and muscle tissue of smelt sampled on the north shore of the St. Lawrence Estuary. The concentrations were relatively low in the muscle tissues. In most of the samples, concentrations of cadmium and lead were lower than the detection threshold. Levels of metal in the liver and gonads were higher, particularly those of copper and zinc. These concentrations point to a low level of metal contamination of this species at the beginning of the 1980s. However, it is impossible to determine the potential effects of this contamination on the population and to evaluate the risks of chronic toxicity.

[20] Saint-Louis, R. and É. Pelletier. 2007. Changements climatiques et composition du macrozooplancton marin : un risque accru à l'exposition au cadmium pour les baleines ? 11e Colloque Annuel du Chapitre Saint-Laurent SETAC/SRA. Rimouski, QC, Mai 2007. Présentation orale.

In the early 1970s, concentrations of mercury in northern shrimp, Pandalus borealis, were 20 times higher than the Canadian Guideline for contaminants in fish and fish products (0.5 $\mu g.g^{-1}$ wet weight). These observations led to the closure of the shrimp fishery in the Saguenay Fjord. The main source of mercury was a chloralkali plant closed in 1976. Since then, mercury concentrations have decreased in shrimps (Cossa 1990).

In the Saguenay Fjord, there is a concern for possible effects of mercury and other metals in predators such as whales. Mercury is potentially immunotoxic[21], genotoxic[22] and neurotoxic[23]. The effects of in vitro exposure of beluga whale splenocytes[24] and thymocytes[25] to different concentrations of mercury chloride were evaluated. The concentrations of total mercury measured in the liver of adult St. Lawrence beluga whales were higher than those that were found to alter the proliferation of beluga whale splenocytes and thymocytes (De Guise et al 1996). The micronucleus assay was used to test the genotoxic potential of mercury compounds in skin fibroblasts[26] of a beluga whale. Significant increases in micronuclei frequency were found at low concentrations of methylmercury (MeHg, 0.05 and 0.5 mg/ml) that are believed to be comparable to concentrations present in the tissues of certain beluga whales (Gauthier et al. 1998).

Mance (1987) and Sorensen (1991) reviewed the various effects of acute and sometimes chronic toxicity on marine organisms, indicating that crustaceans and fish are sensitive to high concentrations of metal in water. This sensitivity varies according to species and stage of development. Certain metals, such as lead and cadmium, have effects on membrane and muscle structures, causing bone and hematological abnormalities in fish.

At an upstream site of the Saguenay Fjord (Baie Éternité) contaminated with heavy metals (Hg, Pb, Zn, Cu), softshell clams (*Mya arenaria*) had lower condition and a delayed gonad maturation compared to a reference sites (Anse St Étienne and Moulin à Baudes) further downstream (Blaise et al. 2002, Gauthier-Clerc 2002). Further studies are needed to identify the source of contamination and to demonstrate cause-effect relationship.

In a more recent and exhaustive study, Gobeil et al. (1997) determined concentrations of mercury, lead, and cadmium in various tissues of fish and crustaceans in the Saguenay Fjord, the Estuary, and the northeast Gulf of St. Lawrence. The highest levels were observed in the Saguenay Fjord. In other places in the St. Lawrence River, concentrations observed in the liver, muscle tissues, and gonads were low and within Canadian standards for human consumption (0.5 mg kg^{-1}, wet weight). However, metal levels in the livers of fish, the hepatopancreas of crustaceans (Rouleau et al. 2001), and the gonads of fish and crustaceans were higher than those found in muscle tissue.

6.6.3 PCBs and other organochlorine contaminants

---

[21] Toxic effects on the functioning of the immune system that result from exposure to chemical substances.
[22] Damaging to DNA: pertaining to agents (radiation or chemical substances) known to damage DNA, thereby causing mutations or cancer.
[23] Having a toxic effect on the nervous system.
[24] Monocytes (type of white blood cell) characteristically found in the splenic tissue.
[25] Lymphocytes (type of white blood cell) arising in the thymus.
[26] A connective tissue cell

Unlike metals, organochlorine contaminants are not found naturally in the environment. Their production and use on an industrial scale date from the 1930s and 40s. They are known for their thermal stability, their resistance to oxidation, and their dielectric properties. By the 1970s, the production and use of a number of these compounds had been limited and even prohibited in Canada. Despite these measures, these compounds, which are resistant to biodegradation, are still found in the environment. These twelve groups of componds belong to a group of persistent organic pollutants (POP) that are the subject of the Stockholm Agreement, ratified by Canada in 2001 and implemented in 2006. They can be bioaccumulated by marine organisms and are found at every level of the food chain.

PCBs (polychlorinated biphenyls) include a range of compounds with the same basic structure but with different combinations of chlorine atoms. There are 209 possible combinations, called "congeners". Among the congeners, some can adopt a coplanary conformation and are recognized to be chiefly toxic. The production and use of PCBs is now restricted in Canada. DDT (dichlorodiphenyltrichloroethane), a pesticide used in agriculture and the forestry industry, was prohibited in Canada in 1985. PCDD/F are mainly the by–products of incomplete combustion of urban and industrial waste containing organochlorine compounds. They are found in the effluents of some pulp and paper mills that use chlorine as a bleaching agent. The quantity of PCDD/F released by these mills has decreased by almost 100% since 1988. Toxaphene is a very complex mixture of chlorine compounds that was used in the United States as a wide–spectrum pesticide to replace DDT. It was banned by several countries, including Canada, at the beginning of the 1980s because of its toxicity. However, toxaphene is one of the most abundant organochlorine pesticides in biota from Great Lakes, western Canada lakes, the Canadian Arctic, and the St. Lawrence Estuary in eastern Canada (Gouteux et al. 2003). Aerial transport appears to be the most likely pathway for the introduction of toxaphene to Canada.

Some compounds present in the Estuary and the Gulf come mainly from the Great Lakes (Cossa 1990, Comba et al. 1993, Lebeuf and Nunes 2005). Other sources are industrial effluents, atmospheric emissions, and diffuse sources. Data on the contamination of sediments and the water column by organochlorines and pesticides are insufficient to build a global image of the contamination in the Estuary and Gulf of St. Lawrence. Research is concentrated more on contamination by PCBs, whose presence in the sediments of the entire St. Lawrence ecosystem was confirmed by Couillard (1982). Gobeil and Lebeuf (1992) determined the total PCB concentrations present in the sediments from three locations in the Lower Estuary. The concentrations observed at the three stations are below the threshold established by the Ontario Ministry of the Environment and Energy (Belles–Isles and Savard 2000). Gobeil and Lebeuf (1992) also estimated that the average rate of PCB accumulation over the years 1980 to 1990 was 450 kg per year in the entire estuary. From data gathered in 1995–1996, Cossa et al. (1997) calculated the annual influx of PCBs (21 congeners) at the level of Québec City. They determined that the quantity of dissolved PCBs in the water entering the Estuary was 54.3 kg per year and the quantity of PCBs adsorbed onto particulate matter in suspension was 124.6 kg per year. Works of Lebeuf and Nunes (2005) confirmed these estimations and reported a cumulative charge of PCB in the Lower St. Lawrence estuary sediment in the order of 8.7 metric tons. Besides, the data indicate a probable decrease of PCB input into the Estuary in the last decades.

The most contaminated zones are generally those situated close to sources, for example, industrial and urban zones. There are several PCB–contaminated sites in the Estuary and Gulf of St. Lawrence. Baie des Anglais is one well–documented case. Lacroix et al. (2001) found that

the concentration of PCBs (sum of 20 congeners) in the contaminated sediments of the Baie was 1500 ng g-1 while in the beach sand, the levels were 13.6 ng g–1 dry weight. In the surface sediments of the Baie, Lee et al. (1999) measured PCB coplanar concentrations of 81.2 ng g–1 of dry sediment, which decreased with distance from the source down to 7.8 ng g–1 of dry sediment.

Lebeuf et al. (1999) determined the levels of PCBs (20 congeners) in the muscle and liver tissues of three species of groundfish in the Estuary and the northeast Gulf of St. Lawrence. The results are within the Canadian standards for consumption of marine products but indicate that fish living in the Estuary have much higher levels of contamination than those living in the northeast Gulf. The effects of the concentrations observed on the health of these organisms remain unknown. Note that PCB levels in liver and muscle tissue are higher than those of DDT, HCB, and mirex.

In high-latitude fish species, a marked seasonal cycle in energy reserves increases vulnerability to persistent contaminants. As fat is mobilized from the storage tissues, the body distribution of contaminants changes and their concentration in target tissues increases leading to an increased risk of toxicity. For example, in large-sized emaciated Atlantic tomcod (*Microgadus tomcod*) sampled in spring in the St. Lawrence Estuary, hepatic PCB concentrations increased as lipid contents decreased and high PCB concentrations were related to suppression of the activity of a liver–CYP1A enzyme, suggestive of an hepatocellular injury. Suppression of CYP1A activity was not observed in large-sized tomcod from two less contaminated estuaries (the Miramichi and Restigouche estuaries, NB), also sampled in spring and having similar low hepatic lipid content but lower PCB concentrations. Further studies are needed to evaluate if hepatocellular injury is associated with impacts on growth, survival, and/or reproduction of the St. Lawrence Estuary tomcod population (Couillard et al. 2004; Couillard et al. 2005). PCBs are endocrine disruptive substance and may affect immune function and reproduction and induce oxidative stress.

Contamination with organochlorine contaminants has been incriminated as a potential cause for the recruitment failure observed in the St. Lawrence American eel in the 1980s (*Anguilla rostrata*) population. As a top predator, eels living in the Lake Ontario/St. Lawrence River accumulated high concentration of dioxin-like compounds including coplanar PCBs, PCDD/F. This group of toxic compound act via a similar toxic mechanisms and the toxic potential of a mixture of these contaminants can be assessed by calculating a 2,3,7,8-tetrachlorooxanthrene or TEQ (TCDD-toxic equivalent concentration, Walker and Peterson 1991). In a 1990 survey of migrating silver eel caught in the St. Lawrence estuary, the range of organochlorinated compounds in eel carcasses were: total PCBs (0.61-2.1 µg/g), chlorinated pesticides (0.23-0.70 µg/g – mostly DDT), and mirex (0.006-0.086 µg/g) (Hodson et al. 1994). Concentrations of PCD and PCDD/F were higher than 110 pg/g TEQ. Predicted concentrations eel eggs would exceed the dose lethal to 100% of trout fry (80 pg/g) (Walker and Peterson 1991), and would cause a major deficit in population-wide recruitment, assuming that eels are as sensitive as lake trout.

Belugas are present year–round in the Estuary and Gulf of St. Lawrence. These animals that have a diversified alimentation feed on fish and occupy a high trophic level. Their lifespan can be 80 years. The composition and concentrations of contaminants found in belugas can therefore give us an idea of the state of their environment. This is apparent in the results of a comparative analysis between animals from the Canadian Arctic and the St. Lawrence Estuary. The St. Lawrence beluga population has organochlorine concentrations much higher than those observed in the Arctic population (Muir et al. 1990). The contamination level of their diet can

possibly explain the difference. Although a recent study showed a decrease of PCD and many other organochlorine compounds in the fat of St. Lawrence belugas between 1987 and 2002 (Lebeuf et al. 2007), there is a concern that organochlorine contaminant could induce endocrine disruption in beluga whales, promote neoplasia or contribute to immune dysfunction (Béland et al. 1993, De Guise et al. 1995 and 1998). Hermaphrodism was observed in stranded beluga whale and is indicative of possible endocrine disruption (DeGuise et al. 1994b). Besides, impaired immune function was observed in rodents fed with blubber of the St. Lawrence Estuary beluga whales (Lapierre et al. 1999, Fournier et al. 2000).

Brochu et al. (1995) studied dioxin (PCDD) and furan (PCDF) contamination in the sediments and biota of two sites in the Lower Estuary: a test site at Baie des Milles Vaches and an industrialized site, Baie des Anglais. Their results indicated low levels of sediment contamination by the two compounds. Higher concentrations were found deeper in the sediment than at the surface (1–2 cm), which indicates a decrease in recent inputs of these two types of compounds in the environment. At both sites, whelks, shrimp, and snow crabs were sampled and their total PCDD and PCDF contents were determined. For the two sites and the two groups of compounds, concentrations found in crabs were higher than in the two other species, but concentrations in all three species were low. Altered immune function and contamination of liver tissue with PCBs was observed in American plaice (Hippoglossoides platessoides) exposed during 3-month to contaminated sediment collected in Baie des Anglais (Lacroix et al. 2001).

6.6.4 Site of the *Irving Whale*

The Irving Whale was a bulk transport barge that sank in the fall of 1970 midway between the Îles–de–la–Madeleine and the coast of New Brunswick at a depth of approximately 70 metres. The barge was transporting a cargo of heavy bunker "C" oil and PCBs were present in the heating system. Following numerous complaints about oil leaking, the wreck was recovered in 1996. A study of contamination at the site by Gilbert et al. (1998) estimated that a total of 5700 kg of PCBs had been released into the environment over the 26 years that the barge was submerged and while it was being raised. Gilbert et al. (1998) also determined that areas of 2353 m2 and 3526 m2 had total PCB concentrations of 100 µg g–1 dry sediment, including areas in which concentrations were over 1000 µg g–1 dry sediment. The area found to be contaminated in 1996 and 1997 was very spread out. The site with PCB concentrations over 100 µg g–1 dry sediment is a fishing exclusion zone and still represents a potential risk for aquatic organisms living in it. Moreover, the wreck is no longer there to act as a barrier to the marine currents that entrain the sediments, as we can see from the increase of the extent of area in which PCB concentrations are higher than 100 $\mu g\ g^{-1}$. In 1996, snow crabs were sampled at the wreck site and in the fishing exclusion zone. Total PCB concentrations in their digestive glands and muscle tissue exceeded the standard of 2 µg g–1 wet weight allowed for human consumption. In 1997, this was no longer the case. While results indicate a decrease in contamination following the salvage operations, it should be taken into account that the environment may have changed between years, as well as the snow crabs since it is not a sedentary species.

6.6.5 Polycyclic aromatic hydrocarbons (PAHs)

PAHs are chemical contaminants that come from natural sources, such as forest fires, or anthropogenic sources, such as aluminium smelters, petroleum and fuel oils and creosote–treated products. Not very soluble in water, PAHs are transported by particulate matter in suspension and are stored in sediments. They are persistent in the St. Lawrence waters. Hundred of PAHs

are presents in the environment. Sixteen of them are included in the Priority Substances List (PSL1) identified in the Canadian Environmental Protection Act (CEPA).

There is little data on the PAH compounds present in the water column and in surface sediments. The only data available was gathered by Antonio Cartosi (Université du Québec à Rimouski, unpublised data) during sampling carried out in 2002–2003. Concentrations of PAHs in surface sediments observed at stations in the Estuary were higher than those observed in the Gulf, at Pointe–des–Monts, and in the Anticosti sector. This trend was reversed when we consider the results obtained from matter in suspension: PAHs concentrations observed at the Pointe–des–Monts and Anticosti stations were higher than those of the stations in the Estuary (Figure 7). The concentrations remain below values that could cause toxic effects. However, it should be noted that even if the total PAHs value is lower than that of the minimal effect level, it does not mean that all the individual PAHs have concentrations below the threshold effect level. From data collected in 1995–1996, Cossa et al. (1997) calculated the annual influx of total PAHs (16 compounds) in the Estuary at the level of Québec City to be 2.2 t of dissolved PAHs and 8.2 t of PAHs adsorbed onto suspended particulate matter.

are belowdetection The effects of PAHs on marine organisms in the St. Lawrence Estuary and GULF are not very well known. Pelletier et al. (1999) determined the PAH concentrations in various tissues of groundfish and crustaceans. Besides, PAH concentrations are below the detection limits in the muscle tissue of cod, Canadian plaice, thorny skate, and black turbot in the Estuary and the Gulf. However, the livers of black turbot in the Estuary and the Gulf are slightly contaminated by benzo[a]anthracene (mean concentration of approximately 8 $\mu g\, kg^{-1}$ wet weight). Also, slight contamination by benzo[a]pyrene was observed in the hepatopancreas of snow crabs captured in the Estuary and analyses of the muscle tissues of northern shrimp in the Estuary and Gulf have revealed fluoranthene, pyrene, benzo[a]anthracene, and phenanthrene.

The low contamination observed in these organisms can be explained by their efficiency in degrading these chemical compounds. Fish are particularly efficient in metabolizing these contaminants. Unlike invertebrates, vertebrates have a group of enzymes that enable them to eliminate a number of chemical molecules, including hydrocarbons. This is also the case for marine mammals. The metabolism of genotoxic PAHs by cytochrome P4501A enzymes generates electrophilic metabolites which bind DNA and causes the formation of DNA adducts. DNA adducts may lead to mutation and to cancer (French et al. 1996).

PAHs have effects on the survival, growth, and reproduction of both invertebrate and vertebrate organisms. They may cause the digestive system tumours observed in some belugas stranded along the St. Lawrence (DeGuise et al. 1994a, Martineau et al. 2002) and the pre–neoplastic lesions observed in the liver of some American eels migrating in the St. Lawrence estuary (Couillard et al. 1997). Exposure to PAHs during development in fish embryos can cause serious abnormalities in the form of malformations (teratogenic effects) and mutations (genotoxic effects) (Couillard 2002).

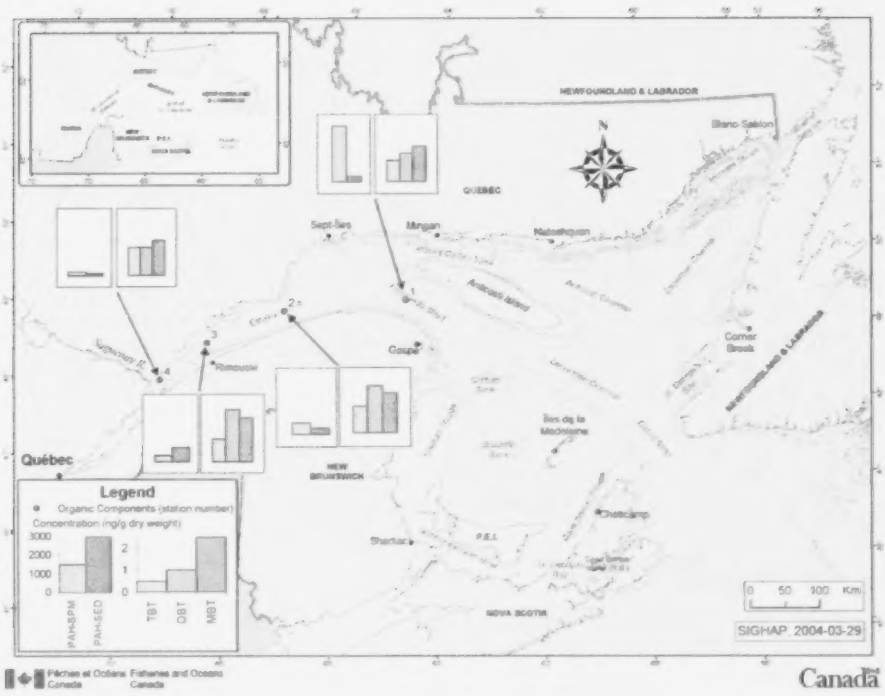

Figure 7. Total PAH in suspended particulate matter (SPM) and surface sediments (SED) observed at four stations and concentrations (ng Sn g^{-1}, dry sediment) of butyltins (TBT, DBT, MBT) in surface sediments of the Lower Estuary and Gulf of St. Lawrence. From Antonio Curtosi, UQAR, Rimouski, QC.

In 1991, two times higher concentrations of metabolites of PAH in the bile and five times higher concentration of bulky DNA adducts in the liver were found in the St. Lawrence Estuary tomcod collected on their breeding grounds in the Batiscan River (QC) compared to Miramichi Estuary tomcod (Wirgin et al. 1994). In contrast, in 2001, tomcods from the St. Lawrence Estuary had similar concentrations of PAH metabolites in the bile and only 1.5 times higher concentrations of DNA adducts in the liver compared to Miramichi Estuary tomcod. Aluminum smelters located on the shore of the St. Lawrence Estuary have been identified as a major source of PAHs and have considerably reduced their emissions of PAHs since 1988 (Couillard et al. 2005).

Martineau et al. (2002) proposed that one important source of exposure of beluga whale could be ingestion of PAH contaminated benthic preys such as polychetes. Recently, the toxicity associated with ingestion of polychetes (Nereis sp.) collected in the beluga whale habitat was assessed using the teleost, Fundulus heteroclitus as a predator. Preliminary results indicate that Nereis collected at different sites in the St. Lawrence beluga whale habitat contain a complex mixture of bio-available chemicals (including PAHs and PCBs) which can cause induction of CYP1A in predators ingesting them and potentially other toxic effects (Couillard et al. 2007).

6.6.6 Organometallic compounds

Organometallic compounds form a relatively little–known family that can be differentiated by the presence of a metal–carbon bond. Tin and mercury form stable organometallic compounds in

the marine environment. Tributyltin (TBT) and its metabolites dibutyltin (DBT) and monobutyltin (MBT) are given particular consideration here. TBT is a powerful biocide with a very wide range of applications. It is especially used in anti–fouling paints to reduce the attachment of algae and invertebrates onto the hulls of ships. In the St. Lawrence Gulf and Estuary, its presence is mainly due to leaching from boat hulls. Urban sewage represents a major source of DBT, an anti–oxidant agent produced through the degradation of plastics. The highest concentrations of butyltins have been found in ports and commercial shipping anchorage areas (Maguire 1992).

A regulation adopted in Canada in 1989 stipulates that only vessels over 25 metres and small aluminium boats may use TBT–based antifouling paints. However, contamination of harbors and areas with high shipping activities is still occurring due to ongoing use of TBT on large vessels and to persistence of TBT in sediments and marine biota. Despite regulations, ecotoxicologically relevant contamination of marine ecosystems is persisting, particularly in sediments (Fent 2006).

There is little data published on levels of TBT in the water column and sediments of the Estuary and Gulf of St. Lawrence. Mamelona and Pelletier (2003) observed concentrations of 9.7 to 13.8 ng Sn l–*1* at Les Méchins on the south shore of the Lower Estuary. There is a large shipyard and a dry dock located in this area. Concentrations of 5 ng Sn l^{-1} have also been observed in the region of Rimouski close to marinas. These results seem low given the proximity to potential sources of TBT.

A recent study (2003) carried out by Marie–Hélène Michaud (Michaud and Pelletier 2006) resulted in the first data on TBT in the sediments of the Estuary and Gulf. The data reveal contamination of sediments in the Laurentian Channel that is 10 to 20 times lower than what has been observed at other sites closer to the shores of the Estuary and Gulf.

Saint–Louis et al. (1997) observed generalized contamination of sediments in the Lower Estuary with total concentrations varying from <1 to 410 ng Sn g^{-1} (dry weight) at Les Méchins, Baie–Comeau, Rimouski Est, Parc National du Bic, and Gros–Cacouna. Sediments and mussels from Les Méchins were the most highly contaminated, with mean TBT concentrations of 40±12 ng Sn g^{-1} in the sediments and 106±37 ng Sn g^{-1} (dry weight) in the mussels.

Pelletier and Normandeau (1997) observed concentrations of butyltins below 50 ng Sn g^{-1} (dry weight) in mussel tissues from sites between Bic and Gaspé. All along the south shore of the Estuary, mussels are exposed to low concentrations of butyltins, the main compound being DBT. Viglino et al. (2006) reported 890-993 ng Sn g^{-1} (dry weight) in bivalves compared 86-239 ng g^{-1}(dry weight) in burrowing dwelling organisms in the Saguenay Fjord. At the same site, the Acadian redfish (Sebastes fasciatus) feeding preferentially on shrimp and small crustaceans rich in TBT had a contamination level about three times higher than eelpout (*Licodes vahlii*) feeding on burrowing species.

As effective biocides, TBT and its derivatives are also toxic to marine organisms and can damage certain organs and hormonal systems. A few hundredths of a nannogram of TBT per litre of water is enough to cause acute toxicity in invertebrate species and plankton and a few milligrams per litre causes an acute toxic reaction in fish. Chronic toxic effects in the form of tissue damage have been observed at concentrations below 1 ng Sn l^{-1} (Fent 1996). Neurotoxic, embryotoxic, hepatotoxic, and immunotoxic effects have also been observed in fish (Fent 1996 and 2006). Recently, androgenic effects of TBT have been reported in fish. Exposure of early life stage of zebrafish (*Danio rerio*) to environmental levels of TBT (1 ng Sn l^{-1}) causes

masculinisation (male biased sex ratio) and irreversible sperm damage (McAllister and Kime 2004). A large variety of organisms, in particular early life stages, are susceptible to low TBT concentrations and bioaccumulation leads to significant exposure of marine biota including marine mammals (Fent 2006). However, the effects of TBT on bivalves are more documented. In bivalves, slowed growth, disruptions to reproduction, and an interference with the ability of oysters to secrete calcium carbonate have been observed (Smith 1981). The most well–known and most spectacular toxic effect is a sexual mutation called imposex, which is observed in gastropods. For example, concentrations of TBT in the tissues of whelks have been correlated with the masculinization of females, meaning the development of male sexual characteristics which impede normal reproduction of the species.

Prouse and Ellis's (1997) work reveals a high frequency of imposex in female whelks in the Gulf and Les Méchins (St. Lawrence Estuary). Imposex was observed at 13 of the 34 sites examined. Moreover, in Sydney (NS), all female whelks with concentrations of 74 ng Sn g^{-1} (wet weight) presented the effects of imposex. Imposex was also observed in whelk collected at two sites located in the Baie des Ha! Ha!: at Port Alfred and at the mouth of the Baie des Ha! Ha! where 53% and 13% of the whelk were affected respectively (Viglino et al. 2006).

Saint–Louis et al. (2000) and Saint–Jean et al. (1999) studied concentrations of TBT, DBT, and MBT in surface sediments and mussels from four sites in the southwest region of the Gulf. The Shediac site was the most highly contaminated. The absence of mussels at this site could be related to the high concentrations of contaminants in the sediments, which may have caused death or inhibited the development of larvae. At other sites, concentrations observed in mussels are between 5 and 671 ng Sn g^{-1} (dry weight). Mussels sampled at the Shediac, Miramichi, Summerside, Pictou, and Cardigan sites have contamination levels that range from moderate to high.

Gagné et al. (2003) reported 109±18 ng Sn g^{-1} (dry weight) in gonads of softshell clams collected in baie Ste Catherine, an intertidal harbour located at the mouth of the Sagueny fjord in the St. Lawrence Estuary. The sex ratio in clams was significantly skewed toward males at this site compared to a control site, Moulin à Baude. Moreover, females collected in Baie Ste Catherine had lower condition and gonadosomatic indices, vitellin-like proteins in their gonads and lower capacity to production of estradiol from their gonad (Gagné et al. 2003 and 2005). Delayed gametogenesis and low progesterone levels was observed in clams collected in Rimouski harbour, located in the St. Lawrence estuary and contaminated with TBT, compared to a reference site, Anse à l'Orignal (Siah et al. 2003).

TBT contamination was observed in the livers of St. Lawrence belugas (Saint–Louis et al. 2000). Total concentrations of TBT varied from 54 ng Sn g^{-1} (dry weight) in a five–year–old female to 2085 ng Sn g^{-1} (dry weight) in a 21–year–old female. The authors also demonstrated that TBT contamination in beluga remained stable in beluga between 1988 and 1998. TBT and DBT also affect immune function in bivalve molluscs. For example, laboratory bioassays revealed dose-dependent changes in cell membrane injury, phagocytic activity, lysosomal retention, and haemocyte count in blue mussels (Mytilus edulis) exposed to very low environmentally realistic concentrations of TBT or DBT (1 ng Sn l^{-1}, St-Jean et al. 1999, 2002a and b). These changes were associated with a reduced ability to clear a foreign bacterium and thus, exposure to butyltins could increase incidence of infectious diseases.

6.6.7 New contaminants

Today, particular molecules used for industrial purposes have physical–chemical characteristics and structures very similar to those of compounds (such as PCBs) that have been prohibited for many years. Exposure to these chemical molecules, whose properties and concentrations in the environment are still practically unknown, poses potential unknown hazards to marine life.

A case in point is that of polybrominated compounds that are used as flame retardants in clothing, carpets, and sofas, and which have a multitude of other domestic and industrial uses. Recent work (Law et al. 2003, Lebeuf et al. 2004a) has revealed that polybrominated diphenyl ether (PBDE) levels in beluga blubber have increased considerably between 1988 and 1999. PBDEs cause thyroid dysfunction, neurological defects, and neurobehavioural toxicity in fish (Timme-Laragy and al. 2006). Safe (1984) demonstrated that the potential toxic action of these molecules could be similar to those of PCBs but that their solubility in water is much lower, which could reduce their consequences. PBDE has the potential to interact with PCBs. Lebeuf et al. (2006) have shown that induction of metabolic activities in tomcod injected intraperitoneally (IP) with PCB126 affected the pattern of bioaccumulation of polybrominated compounds and potentially their toxicity to fish.

Sometimes, attention and analytical effort is concentrated only on a chemical "mother" molecule, when in fact it can be metabolized and some of the metabolites are more bioavailable. For example, the principal metabolites of DDT degradation are DDD (dichloro-diphenyl-dichloro-ethane) and DDE (1,1-dichloro-2,2-bis(4-chlorophenyl)ethene), which today are the dominant types of DDT compounds present in marine mammals. However, we know little about their properties in the marine environment. Another example is that of the PAH metabolites, which have been analyzed very little in the organisms of the Estuary and the Gulf although some researchers believe that they are carcinogenic to belugas. Besides, PCB and polybrominated compounds metabolites have recently been reported on St. Lawrence beluga whales at higher levels than on the arctic beluga whales (McKinney et al. 2006).

There are also other non–chemical contaminant sources that can cause harmful effects to marine organisms in the St. Lawrence that have not been mentioned in this report due to a lack of available data. These sources include:

1) urban waste, which contains other types of organic molecules (such as pharmaceuticals, estrogens and hormones) and which can affect the life cycles of all marine organisms. Furthermore, urban waste introduces pathogenic bacteria, viruses, and parasites, whose behaviour in the marine environment is almost completely unknown;

2) agricultural waste, which contains large quantities of organic matter, nitrates, and phosphates as well as some pesticides and herbicides that have not yet been clearly identified in the marine environment. In addition, this type of contamination is not very well documented.

In July and August 2002, concentrations of pesticides were measured in the water of 8 freshwater tributaries located on the south shore of the St. Lawrence Estuary, from St. Roch-des-Aulnaies to Pointe-au-Père. Nine pesticides were detected at low concentrations (<1.7 $\mu g\ l^{-1}$). The highest concentrations of pesticides (Dicamba, Mecoprop, MCPA, 2,4-D et 2,4-DB) were found at Trois Pistoles and Pointe-au-Père. Atrazine was detected at Isle-Verte and Kamouraska at levels up to 0.16 $\mu g\ l^{-1}$. In 2003, water from 4 sampling sites, Isle-Verte, Trois Pistoles, Bic and Pointe-au-Père were sampled on 10 occasions between May and September. Eight pesticides were detected

at low frequency with peak concentrations generally found early July. The most frequently detected pesticides were Simazine, Metolachlore and 2,4-D while atrazine was not detected at any of the sites. Only carbofuran was detected in our control site (Bic). Water concentrations were below the current chronic toxicity guidelines for the protection of aquatic organisms (Lebeuf et al. 2004b).

In the North Atlantic, short-term exposure of young Atlantic salmon (Salmo salar) to endocrine disrupting substances in their freshwater natal environments later leads to detectable effects on their growth and survival at the time of their migration to saltwater. Fairchild et al. (1999) noted a relationship between aerial spraying with Matacil® in the forests of Atlantic Canada and subsequent returns of salmon between 1975 and 1985. This problem was associated to a solvent used in the pesticide formula, 4-nonylphenol (4-NP) which is an endocrine disruptive compound. Two 24-h pulse-exposures to 4-NP during the late stage of smoltification induced experimentally an increased proportion of salmon showing poor growth during the first 5 months in seawater (Fairchild et al. 2002). Other toxic chemicals including the widely used herbicide atrazine have been recently shown to cause delayed impact on the capacity of Atlantic salmon to adapt to seawater (Waring and Moore 2004). Fortin et al. (2007) have shown that a short term exposure to environmentally realistic concentrations of atrazine affected osmotic control in mummichog (Fundulus heteroclitus) larvae with possible effects on buoyancy, survival and recruitment.

6.7 COASTAL EUTROPHICATION

Eutrophication of coastal waters results from excessive input of organic waste and nutrients. Organic wastes discharged into the marine environment are usually in the form of particulate matter that is eventually decomposed and usually assimilated by the marine ecosystem. However, high loads of organic matter can cause oxygen depletion, lower habitat productivity and anoxic chemical pollution when the capacity of the environment to decompose aerobically is exceeded. This can result in the displacement of fish and other organisms, the killing of benthic life, and changes to the food web. Ultimately, high or continued loading can cause the loss of oxygen and habitat productivity.

Estuarine ecosystems are complex and uniquely adapted. A combination of low tidal amplitude, layering of the water column, relatively low river flows, and the deep–water fjord structure of some smaller estuaries can contribute to restricted water circulation and slow replenishment of oxygen. For example, the predictable occurrence of warmer waters with rapid production of prey organisms and the restricted exchange with offshore waters makes St. Georges Bay in Cap–Breton a successful nursery ground for pelagic spawners (Hargrave et al. 1985).

There are clear indications that the ecology of some estuaries is being changed by organic input where agriculture and urban development are a major features of the watershed. This can be seen in changes in the nutrient composition and balance, in the depletion of oxygen, and in the increased growth of macrophytes and algae mats.

6.7.1 Organic waste and nutrients associated with land–based activities

The major input of organics and the resulting nutrients in coastal Atlantic Canada is from the discharge of raw or partially treated municipal sewage into rivers, estuaries, and harbours. Point sources include municipal wastewater, industrial effluents from pulp mills and fish plants, and combined sewer overflow, where street runoff is combined with sewage. The absence of individual septic systems or poorly maintained ones are another source of organic waste.

Agricultural fertilizers and livestock are predominant sources of non–point source runoff that result in coastal and estuarine problems.

Nutrient problems are closely linked with the organic input and bacterial contamination described above, and they are almost always found together. This has resulted in the closure of many shellfish beds and swimming areas as well as fouling of wildlife habitats, as in Lameque Bay, NB. Where the best management practices are used, the impacts can be reduced to within natural ranges.

The largest single source of freshwater input into the Estuary and the Gulf of St. Lawrence is the St. Lawrence River. It flows from the most populated areas in Canada. This water carries with it a substantial amount of organic matter that varies somewhat with discharge but remains relatively unchanged on an annual basis (Pocklington 1988). There are clear indications that the ecology of some smaller estuaries is being modified by organic input, especially where industrial activity, agriculture and urban development are major features of the watershed. For example, in the Saguenay Fjord in the Lower St. Lawrence Estuary, accumulated deposits of wood fibre (lignin) in sediments close to the mouth of the river are directly linked to the region's pulp and paper industry (Louchouarn et al. 1997). There are approximately 20 pulp and paper mills in the drainage basin of the Gulf of St. Lawrence. Lignin concentrations in the open areas of the Gulf are close to zero (Pocklington 1988).

A combination of micro–tidal amplitude, stratified water column, and relatively low river flows creates low flushing conditions in estuaries. The fjord structure of some estuaries in Newfoundland causes conditions of low water circulation and slow replenishment of oxygen. These locations are particularly sensitive to organic loading. Areas where municipal sewage and industrial outflows are close to each other pose a high risk of impacts on the ecosystem. In the southern Gulf of St. Lawrence, nutrients from agricultural sources present a significant problem, particularly where the flow pattern in estuaries has been disrupted by the construction of causeways and dikes.

Eutrophication of coastal waters resulting from this excessive input of organic waste and nutrients is a particularly critical problem in coastal waters around Prince Edward Island. Here the addition of agricultural fertilizers has led to enriched groundwater and eutrophication of upper estuarine waters. Data show that nitrate levels in three Prince Edward Island river systems have increased several folds over the past 30 years. Water quality in these systems is not influenced by point sources; the major sources are agricultural fertilizers and livestock manure.

Excessive phytoplankton and macroalgal growth, like the appearance of algal mats and sea lettuce (*Ulva lactuca*) in the inter–tidal zone, are indicators of excessive nutrient loading. The massive decay of plant material in areas of low mixing or in areas that tend to stratify can result in oxygen depletion and in the production of toxic gases such as hydrogen sulphide and ammonia. Fish kills will occur only in extreme cases, where algal growth has depleted oxygen to critical levels.

High nutrient levels in surface waters may also be a major contributing factor in harmful algal blooms (HABs). Toxic algal blooms, such as *Pseudo–nitzschia fraudulenta* that result in excess domoic acid accumulation in bivalve shellfish, can result in human illnesses such as Paralytic and Diarrhetic Shellfish Poisoning (PSP and DSP) and, in the worst–case scenario, can result in deaths. These incidents of contamination are cyclic in nature and occur, with varying levels of toxin production, throughout the coast of eastern Canada each year.

7.0 SPECIES OF CONCERN

7.1 MARINE FISH

The marine fish communities in the Gulf have experienced dramatic changes in the relative abundance of their component species over the last 30 years. Many of the large–bodied groundfishes declined to very low levels in the 1990s (e.g., cod, redfish, white hake, American plaice, and skates). In contrast, many pelagic fishes were at relatively high levels of abundance throughout much of the 1990s and early 2000s (e.g., herring, capelin, and mackerel). Thus, in both the southern and northern Gulf ecosystems, there has been a substantial increase in the importance of pelagic fishes relative to groundfishes in the 1990s and 2000s. In contrast to most groundfishes, abundance increased in the 1990s for some deepwater flatfishes, notably Greenland and Atlantic halibut and witch flounder. These increases reflect strong recruitment in the 1990s. In the southern Gulf, where there is a long time series of consistent trawl survey data, other dramatic changes in the ecosystem are evident (H. P. Benoît and D. P. Swain, Gulf Fishery Center, Moncton, NB, unpublished analyses). A number of coldwater species (e.g., arctic cod, polar and arctic sculpins) increased temporarily in the mid 1990s, during a prolonged period of cold bottom waters in the southern Gulf. But most notable has been an increase in the abundance of many small–bodied species in the late 1980s and the 1990s. These changes in species composition have resulted in a large shift in the biomass spectrum of the fish community in the southern Gulf, with declines in the biomass at large sizes and increases at small sizes.

The decline in the abundance of large–bodied groundfishes is thought to be mainly due to overfishing, though for some species (e.g., cod) declines in productivity also appear to play a role. Cod productivity was high in the late 1970s and early 1980s, primarily because of an unusually high rate of recruitment. In the southern Gulf in the 1990s, the recruitment rate of cod had declined to average levels, the growth rate was low, and natural adult mortality was high, about twice the normal level for cod. Given its current low productivity, no recovery of the southern Gulf cod stock is expected, even in the absence of fishing. Mackerel and herring were at very low levels in the mid to late 1970s, likely the result of heavy fishing in the late 1960s and early 1970s. The increase in the biomass of these pelagic fishes throughout the 1980s may reflect a recovery from overfishing following declines in their exploitation rates in the late 1970s. The recent increase in the abundance of small–bodied fishes in the southern Gulf may reflect a release from predation following the decline in large–bodied predatory fishes. Significant environmental changes have also occurred over the last 30 years. Bottom waters on the shelves were relatively warm in the late 1970s and early 1980s. The cold intermediate layer (CIL) in the Gulf underwent a prolonged cooling from the late 1980s to the mid 1990s. In the late 1990s and early 2000s, spring temperature conditions have been unusually warm, with 1999 the warmest spring in the 50–yr record. The effects of these environmental changes on the fish communities in the Gulf are uncertain.

COSEWIC has recognized four populations of Atlantic cod in Canada, in accordance with available genetic, ecological, and demographic information (COSEWIC 2003). Two of these populations occur in the Gulf of St. Laurence: the Laurentian North population, which is found north of the Laurentian Channel in the Gulf of St. Lawrence and along the south coast of Newfoundland, and the Maritimes population, which is found in the southern Gulf, the Scotian Shelf and the Gulf of Maine. Laurentian North cod are at or near historically low levels of abundance, following an over 80% decline in abundance over three generations. This has led

COSEWIC to recommend a designation of threatened for this population. The decline has been less pronounced for the Maritimes population (14% over three generations), leading to a recommended special concern status designation by COSEWIC. These populations were submitted for Governor in Council consideration for official designation under SARA in January 2005. Threats to persistence of both of these populations include fishing (directed and bycatch), predation, as well as natural and fishing–induced changes to the ecosystem. A small cod directed fishery is allowed in the southern and northern Gulf of St. Lawrence since 2004, following a one year moratorium.

In 2004, there were three species of wolffish and two populations of cod in the Gulf of St. Lawrence for which there was official concern over their conservation status. The northern wolffish (*Anarhichas denticulatus*) and the spotted wolffish (*A. minor*) are listed as threatened species on Schedule 1 of SARA. Over three generations, the abundance of these two species has declined by over 90% and the extent of distribution has also decreased. Specific threats for these species are believed to include bycatch mortality in commercial fisheries and habitat alteration by bottom trawling, ocean dumping and other sources of pollution, all of which may be compounded by environmental change (Wolffish Recovery Team 2003). Northern wolffish are a bathypelagic species feeding on pelagic prey such as ctenophores and medusas as well as a variety of benthic invertebrates (Albikovskaya 1983). In the Gulf, they are found mainly in waters deeper than 150 m, off the south and west coasts of Newfoundland (Nozères and Bérubé 2003, Wolffish Recovery Team 2003). Spotted wolffish feed on krill and other crustaceans such as echinoderms, mollusks, and opportunistically on small fishes (Albikovskaya 1983, Scott and Scott 1988). In the Gulf, they occur mainly at depths of 100–350 m in the Esquiman and Anticosti channels, and the northern portion of the Laurentian Channel (Nozères and Bérubé 2003, Wolffish Recovery Team 2003).

The status of Atlantic wolffish (*A. lupus*) was designated as being "of special concern" by COSEWIC in 2000, as a result of a decline in abundance in a portion of the species range. It is listed on schedule 1 of SARA. The purported threats to this species are the same as for the other wolffishes. The Atlantic wolffish diet is mainly composed of hard–shelled benthic invertebrates such as echinoderms, molluscs and crustaceans, but it also eats small amounts of other fish (Albikovskaya 1983, Templeman 1985). In the Gulf, they are distributed along the slopes of the Laurentian, Esquiman and Anticosti channels (McRuer et al. 2000).

7.2 DIADROMOUS FISH

There are currently no species of special concern as identified by COSEWIC. Three species are currently under review: Atlantic sturgeon (*Acipenser oxyrhynchus*), striped bass (*Morone saxatilis*), and American shad (*Alosa sapidissima*).

7.3 MARINE MAMMALS

In the present section, only marine mammals that occur in the Saguenay Fjord and St. Lawrence Estuary will be discussed: beluga whale, harbour porpoise, fin whale, blue whale, and harbour seal.

7.3.1 Beluga whale population status (Threatened)

The St. Lawrence beluga population has decreased significantly over the last century. At the end of the 1800s, the number of belugas was estimated to be between 5,000 and 10,000 animals

(Reeves and Mitchell 1984, Béland et al. 1988). By the end of the 1970s, however, the population had declined to only 10% of what it was in 1885. This population decline was mainly related to large–scale hunting. In the 1930s, the provincial government allocated hunting premiums for the elimination of 1,826 animals because they were believed to be important predators of commercially exploited fish species (Vladykov 1944). In 1979, the population was allocated the status of Protected Species and hunting was prohibited (Sergeant 1986). In 1983, the population was classified as Endangered by COSEWIC, and this status was maintained after revision in 1997 (Lesage and Kingsley 1998). An aerial survey conducted in 2000 estimated the St. Lawrence population to be 952 individuals with a correction factor of 109% to account for animals that were not visible at the surface of the water during the survey (Gosselin et al. 2001). The last re–examination of this population's status in May 2004 reassigned them to the less critical "Threatened" category under SARA and COSEWIC.

An evaluation of the potential population increase of the St. Lawrence beluga whales has been attempted in several papers (Béland et al. 1988, Michaud 1993, Desrosiers 1994, Kingsley and Reeves 1998). The variability associated with the different survey estimates makes it difficult to detect real changes in abundance (Gosselin et al. 2001). A population estimate is dependent on the distribution of the animals and the proportion of the population that is surveyed (Smith and Hammill 1986). According to the last estimated population indices conducted between 1988 and 2000, it seems that the beluga population has remained stable (Gosselin et al. 2001).

Some measures have been undertaken in the St. Lawrence Estuary to protect the beluga whales and their habitat. In 1996 (St. Lawrence beluga recovery team 1995), a recovery plan was established and later revised in 1998 (St. Lawrence beluga recovery committee 1998). The goal of this plan was to increase the beluga population to a level such that natural events and human activities will not be threats to its survival. The plan will need to be revised again in order to be in accordance with SARA. In addition, to protect beluga calving and feeding grounds, the mobile–gear scallop fishery upstream of the Saguenay mouth has been prohibited since 1999. Blasting and dredging activities are also restricted in certain areas of the St. Lawrence Estuary.

7.3.2 Harbour porpoise population status (Special Concern)

The northwest Atlantic harbour porpoise population was assigned a Special Concern status (Schedule 2) by SARA. This species is not likely to be designated as Threatened or Vulnerable either under Québec law or as a priority species requiring protection under the St. Lawrence Vision 2000 Action Plan (outgrowth of a Canada-Québec agreement on the St. Lawrence for a sustainable development 2005-2010).

Aerial surveys conducted in 1995 and 1996 over a large portion of the Gulf of St. Lawrence (but which did not extend into the St. Lawrence Estuary) estimated the number of harbour porpoises to be between 12,100 animals (SE = 3,200) in 1995 and 21,720 animals (SE = 8,360) in 1996 (Kingsley and Reeves 1998). These represent minimal estimates because they were not corrected for animals below the surface of water and therefore missed during surveys.

7.3.3 Fin whale population status (Special Concern)

The North Atlantic fin whale population is listed as Special Concern under SARA. In Québec, it is listed as a species likely to be designated as Threatened or Vulnerable under Québec law. However, the St. Lawrence Vision 2000 Action Plan's list did not assign it as a priority species requiring protection.

In the St. Lawrence Estuary, no precise population estimates or data on the population dynamics are available for the fin whale. According to R. Michaud (GREMM, Tadoussac, QC, personnal communication), about a hundred different individuals can be observed during a season. Their numbers vary among seasons due to euphausiid availability. Since 1985, a hundred fin whales have been photoidentified in the Estuary.

Aerial surveys conducted in the Gulf of St. Lawrence, excluding the Estuary, estimated the number of fin whales to be between 380 (SE = 300) in 1995 and 340 (SE = 240) individuals in 1996 (Kingsley and Reeves 1998). However, these estimates are uncorrected for whales below the surface of water and therefore missed during surveys and thus represent minimal population estimates.

7.3.4 Blue whale population status (Endangered)

The North Atlantic blue whale population is listed as Endangered under COSEWIC. In Québec, it is listed as a species likely to be designated as Threatened or Vulnerable under Québec law. However, it is not a priority species requiring protection under the St. Lawrence Vision 2000 Action Plan. Since it was assigned the endangered status designation, experts have been working on the establishment of a recovery strategy that should be completed by 2006–2007.

The number of blue whales present in the St. Lawrence Estuary is not well known. Since 1979, about 396 individuals have been photographically identified in eastern Canada, among which 90% were within the St. Lawrence River. There are limited observation efforts outside the St. Lawrence River, but all of the animals identified are believed to be part of the same population.

7.4 SEALS

There are no seals in the St. Lawrence River that had received a designation status by COSEWIC as of November 2003. However, the Atlantic population of harbour seals was evaluated in April 1999 and the relatively poor information on this seal population led COSEWIC to assign a designation of Data Deficient in 2005. However, they are believed to be At Risk in the St. Lawrence Estuary[27].

7.4.1 Harbour seal (Data Deficient)

As mentioned, harbour seals of the St. Lawrence Estuary are believed to be at risk. However, there are several uncertainties related to this species that prevent an accurate status designation. An Action Plan was published recently in order to protect and to show the value of this species and its habitat.

The harbour seal population of eastern Canada underwent a notable reduction during a premium hunting program supported by the government between 1927 and 1976 (Boulva and McLaren 1979). This program was banned in 1976, and since then the Harbour seal has been protected over its entire range in eastern Canada. Population estimates obtained in the 1970s from

---

[27] ROMM (Réseau d'observation de mammifères marins). 2004. Plan d'action sur le phoque commun (Phoca vitulina concolor) de l'estuaire du Saint-Laurent. Rapport produit pour le ministère des Pêches et des Océans du Canada et le parc marin du Saguenay–Saint-Laurent en collaboration avec les partenaires de la table de concertation sur le phoque commun de l'estuaire du Saint-Laurent.

questionnaires sent to fishery officers suggest that about 700 harbour seals were present in the St. Lawrence Estuary and Saguenay Fjord at that time (Boulva and McLaren 1979). However, this survey was not exhaustive. During aerial surveys conducted in the Estuary and Saguenay Fjord from 1994 to 1997, and in 2000, seal numbers ranged from 389 to 659 individuals. Although the surveys were conducted at the time when the highest number of seals were out of the water, there is always an unknown proportion of animals in the water and therefore not visible. A model to correct for the number of animals in the water during aerial surveys is presently under development. This model will allow the calculation of a population trend and therefore provide a better overview of the status of harbour seals in the St. Lawrence Estuary.

7.5 MACROPHYTES

In 1992, it was estimated that close to 374 of the 1850 Québec indigenous plant species were potentially considered threatened or vulnerable[28]. Among these, about 65% were found along a corridor covering a shoreline band of 1 km wide on either side of the St. Lawrence Estuary (Lavoie 1992).

Ten species of riparian and aquatic plants are of concern in the Saguenay Fjord and St. Lawrence Estuary. In the Saguenay Fjord and the Gulf, this list might be an underestimate due to the limited number of studies conducted in the area. The major threats for these plant species are habitat loss, off–track vehicle circulation, and shearing of the shore–grass on the littoral (Environment Québec 2004, SARA 2005).

[28] Lavoie, G. 1992. Plantes vasculaires susceptibles d'être désignées menacées ou vulnérables au Québec. Ministère de l'Environnement du Québec, Direction de la conservation et du patrimoine écologique, Québec.

Tableau 1. List of the main stressors resulting from human

ACTIVITY	SUB–ACTIVITY	Habitat destruction	Biomass removal	Spills	Wastes/sewage
Fisheries	Fishing	X	X	X	X
	Fish processing plants				X
Aquaculture					
Marine transportation	Waterways				
	Shipping			X	X
	Coastal infrastructures	X			
Hydroelectric development	Dams / Water diversions				
Human settlement	Coastal infrastructures	X			
	Municipalities				X
Industrial activities					X
Agriculture					
Offshore Oil and gas	Seismic exploration				
	Exploratory drilling	X			X
	Exploitation	X		X	X
Multiple oriented activities having an impact on climate change					
Recreational activities	Boating			X	
	Eco–tourism				
	Shore activities	X			

human activities in the Estuary and Gulf of St. Lawrence.

STRESSORS																	
Spills	Wastes/sewage	Parasites/diseases	Invasive species	Nutrients/organic matter	Dredging	Disposal at sea	Freshwater inputs	Collisions	Disturbance (sound, treshold)	Current obstruction	Contaminants	Produced waters	Meteorological Forcing	Currents/water masses	Coastal water levels
X	X														
	X	X	X												
		X	X	X											
					X	X	X								
X	X		X					X	X		X				
										X					
				X			X				X				
										X					
	X			X							X				
	X			X							X				
				X			X				X				
									X						
	X								X						
X	X			X					X		X	X			
							X						X	X	X
X								X	X						
									X						
									X						

8.0 ACKNOWLEDGEMENTS

This document is a review and synthesis of many working documents, most of which are not yet published, that are well documented and written with the purpose of covering all the subjects contained in this report in a more detailed way. Many persons took part directly or indirectly in this project; the following is a list of the main reviewers who worked on this synthesis report:

D. Cairns, D. Chabot, C. Couillard, S. Courtnay, M.–F. Dalcourt, J.–D. Dutil, C. Foley, A. Fréchet, P. Galbraith, D. Gascon, L. Gendron, M. Giguère, D. Gilbert, M. Hanson, M. Harvey, É. Lagacé, P. Larouche, J. Lawson, M. Lebeuf, D. Lefaibre, V. Lefouest, I. McQuinn, V. Moulton, C. Mullins, S. Plourde, J. Rice, L. Savard, C. Savenkoff, G. Sharp, M. Starr, N. Templeman, J.–C. Therriault and G.H. Tremblay.

We would also like to thank, Anne–Marie Cabana (Maurice-Lamontagne Institut, Mont-Joli, QC) for the coordination of a first edition of the original texts. Many thanks also to Laure Devine (Maurice-Lamontagne Institut, Mont-Joli, QC) and Louise Gendron (Maurice-Lamontagne Institut, Mont-Joli, QC), who edited the English and French versions respectively and, finally, to Claude Savenkoff (Maurice-Lamontagne Institut, Mont-Joli, QC) who, at the end, patiently reviewed the last French version.

9.0 REFERENCES

ACIA. 2005. Arctic Climate Impact Assessment. Symon C. (editor). Cambridge University Press, Cambridge.

Albikovskaya, L.K. 1983. Feeding characteristics of wolffishes in the Labrador–Newfoundland region. NAFO Sci. Coun. Studies 6: 35–38.

Ardisson, P.–L., and E. Bourget. 1991. Abundance, growth, and production estimation of blue mussel *Mytilus edulis* on moored navigation buoys in the Estuary and northwestern Gulf of St. Lawrence. Can. J. Fish. Aquat. Sci. 48: 2408–2419.

Ardisson, P.–L., and E. Bourget. 1992. Large–scale ecological patterns: discontinuous distribution of marine benthic epifauna. Mar. Ecol. Prog. Ser. 83: 15–34.

Ardisson, P.–L., and E. Bourget. 1997. A study of the relationship between freshwater runoff and benthos abundance: a scale–oriented approach. Est. Coast. Shelf Sci. 45: 535–545.

Ardisson, P.–L., E. Bourget and P. Legendre. 1990. Multivariate approach to study assemblages at large spatio–temporal scales: the community structure of the epibenthic fauna of the Estuary and Gulf of St. Lawrence. Can. J. Fish. Aquat. Sci. 47: 1364–1377.

Arnac, M., et C. Lassus. 1985. Accumulation de quelques métaux lourds (Cd, Cu, Pb et Zn) chez l'éperlan (*Osmerus mordax*) prélevé sur la rive Nord de l'estuaire du Saint–Laurent. Water Res. 19: 725–734.

Bailey, R.F.J., and R.W. Elner. 1989. Northwest atlantic snow crab fisheries: lessons in research and management. *In* Marine invertebrate fisheries: their assessment and management. *Edited by* J.F. Caddy. John Wiley and Sons, New-York. pp. 261–280.

Bailey, R.F.J., K.W. Able and W.C. Leggett. 1977. Seasonal and vertical distribution and growth of juvenile and adult capelin (*Mallotus villosus*) in the St. Lawrence Estuary and western Gulf of St. Lawrence. Can. J. Fish. Aquat. Sci. 34: 2030–2040.

Banks, R.E. 1966. The cold layer in the Gulf of St. Lawrence. J. Geophys. Res. 71: 1603–1610.

Beamish, F.W.H. 1980. Biology of the North American anadromous sea lamprey, *Petromyzon marinus*. Can. J. Fish. Aquat. Sci. 37: 1924-1943.

Béland, P., A. Vézina and D. Martineau. 1988. Potential for growth of the St. Lawrence (Québec, Canada) beluga whale (*Delphinapterus leucas*) population based on modelling. ICES J. Mar. Sci. 45: 22–32.

Béland, P., S. DeGuise, C. Girard, A. Lagace, D. Martineau, R. Michaud, D.C.G Muir, R.J. Norstrom, E. Pelletier, S. Ray and L.R. Shugart. 1993. Toxic compounds and health and reproductive effects in St. Lawrence beluga whales. J. Great Lakes Res. 19(4) : 766-775.

Belles–Isles, J.–C., et J.–P. Savard. 2000. Élaboration d'un plan de travail pour la révision des critères intérimaires de la qualité des sédiments et détermination des bruits de fond de certains métaux et HAP dans le Saint–Laurent. Volet 1. Plan de travail du processus de révision des critères de qualité. Volet 2. Évaluation de la pertinence des bruits de fond. Groupe conseil Génivar inc.

Bérard–Therriault, L., M. Poulin et L. Bossé. 1999. Guide d'identification du phytoplancton marin de l'estuaire et du golfe du Saint–Laurent incluant également certains protozoaires. Publ. spéc. can. sci. halieut. aquat. 128. 387 p.

Berkes, F. 1982. Preliminary impacts of the James Bay hydroelectric project, Québec, on estuarine fish, and fisheries. Arctic 35: 524–530.

Blaise, C., F. Gagné, J. Pellerin, P.-D. Hansen and S. Trottier. 2002. Molluscan shellfish biomarker study of the Quebec, Canada, Saguenay fjord with the soft-shell clam, *Mya arenaria*. Environ. Toxicol. 17(3): 170-86.

Blanchard, F. 2001. The effect of fishing on demersal fish community dynamics: an hypothesis. ICES J. Mar. Sci. 58: 711–718.

Blane, J.M., and R. Jaakson. 1994. The impact of ecotourism boats on the St. Lawrence Beluga Whales. Environ. Con. 21(3): 267–269.

Blasco, D., L. Bérard–Therriault, M. Levasseur and E. Vrieling. 1996. Temporal and spatial distributions of the ichthyotoxic dinoflagellate *Gyrodinium aureolum* Hulburt in the St. Lawrence, Canada. J. Plankton Res. 18: 1917–1930.

Boulva, J., and I.A. McLaren. 1979. Biology of the harbor seals, *Phoca vitulina* in eastern Canada. Bull. Fish. Res. Board Can. 200: 1–24.

Bourgault, D., and V.G. Koutitonsky. 1999. Real–time monitoring of the freshwater discharge at the head of the St. Lawrence Estuary. Atmosphere–Ocean 37: 203–220.

Bourgault, D., D.E. Kelley and P.S. Galbraith. 2005. Interfacial solitary wave run–up in the St. Lawrence Estuary. J. Mar. Res. 63: 1001–1015.

Bourget, E. 1997. Les animaux littoraux du Saint–Laurent: guide d'identification. Les presses de l'Université Laval, Québec, QC. 268 p.

Bourget, E., L. Lapointe, J.H. Himmelman and A. Cardinal. 1994. Influence of physical gradients on the structure of a northern rocky subtidal community. Ecoscience 1(4): 285–299.

Bourget, E., P.–L. Ardisson, L. Lapointe and G. Daigle. 2003. Environmental factors as predictors of epibenthic assemblage biomass in the St. Lawrence system. Estuar. Coast. Shelf Sci. 57(4): 641–652.

Brêthes, J.–C., G. Desrosier and F. Coulombe. 1982. Food of the snow crab (*Chionoecetes opilio*) from the southwestern part of the gulf of St. Lawrence. *In* Proceedings of the international symposium on the genus *Chionoecetes*. May 3–6, 1982. *Edited by B. Melteff.* Lowell Wakefield Symposia series. pp. 319–335.

Brickman, D., and B. Petrie. 2003. Nitrate, silicate and phosphate atlas for the Gulf of St. Lawrence. Can. Tech. Rep. Hydrogr. Ocean Sci. (*English only*). 231: xi + 152 p.

Brochu, C., S. Moore and E. Pelletier. 1995. Polychlorinated dibenzo–p–dioxnis and dibenzofurans in sediments and biota of the Saguenay Fjord and the St. Lawrence Estuary. Mar. Pollut. Bull. 30: 515–523.

Brunel, P., L. Bossé et G. Lamarche. 1998. Catalogue des invertébrés marins de l'estuaire et du golfe du Saint–Laurant. Publ. spéc. can. sci. halieut. aquat. 126: 405 p.

Bugden, G.L. 1991. Changes in the temperature–salinity characteristics of the deeper waters of the Gulf of St. Lawrence over the past few decades. *In* The Gulf of St. Lawrence : small ocean or big estuary ? *Edited by J.-C. Therriault.* Publ. spéc. can. sci. halieut. aquat. 113: 139–147.

Bugden, G.L., B.T. Hargrave, M.M. Sinclair, C.L. Tang, J.–C. Therriault and P.A. Yeats. 1982. Freshwater runoff effects in the marine environment: the Gulf of St. Lawrence example. Can. Tech. Rep. Fish. Aquat. Sci. 1078, 88 p.

Bundy, A. 2005. Structure and functioning of the eastern Scotian Shelf ecosystem before and after the collapse of groundfish stocks in the early 1990s. Can. J. Fish. Aquat. Sci. 62: 1453–1473.

CAFSAC. 1994. Rapport sur l'etat des stocks de poissons de fond canadiens dans l'Atlantique nord–ouest. MPO, Rapp. état stocks 94/4.

Cairns, D.K., G. Chapdelaine and W.A. Montevecchi. 1991. Prey exploitation by seabirds in the Gulf of St.Lawrence. *In* The Gulf of St. Lawrence : small ocean or big estuary ? *Edited by J.-C. Therriault.* Publ. spéc. can. sci. halieut. aquat. 113: 277–291.

Cardinal, A. 1990. Biogeographic distribution of benthic marine algae on the coast of Québec. Naturaliste canadien 117: 167–182.

Caron, L.M.J., and D.E. Sergeant. 1988. Yearly variation in the frequency of passage of beluga whales (*Delphinapterus leucas*) at the mouth of the Saguenay River, Québec, over the past decade. Naturaliste canadien 115(2): 111–116.

Carpenter, S.R., J.F. Kitchell and J.R. Hodgson. 1985. Cascading trophic interactions and lake productivity. BioScience 35: 634–639.

Castonguay, M., Y. de Lafontaine and J.A. Runge. 1998. Annual and spatial variability in zooplankton biomass and species composition, and in eggs and larvae of mackerel and cod in the southern Gulf of St. Lawrence between 1982 and 1991. Can. Stat. Rep. Sci. Halieut. Aquat. 1035: v + 86 p.

CDEENA. 2003. Web site of Comparative Dynamics of Exploited Ecosystems in the Northwest Atlantic. [Online] available from http://www.osl.gc.ca/cdeena/en/accueil.shtml, [accessed Décembre 2003].

Chabot, R., et A. Rossignol. 2003. Algues et faune du littoral du Saint–Laurent maritime : guide d'identification. Institut des sciences de la mer de Rimouski, Rimouski, et Pêches et Océans Canada, Institut Maurice–Lamontagne, Mont–Joli, 113 p.

Chadwick, M., and A. Sinclair. 1991. Fisheries production in the Gulf of St. Lawrence. *In* The Gulf of St. Lawrence : small ocean or big estuary ? *Edited by J.-C. Therriault.* Publ. spéc. can. sci. halieut. aquat. 113: 125-136.

Chapdelaine, G. 1995. Fourteenth census of seabird populations in the sanctuaries of the north shore of the Gulf of St. Lawrence, 1993. Can. Field–Nat. 109(2): 220–226.

Chapdelaine, G., and P. Brousseau. 1991. Thirteenth census of seabird populations in the sanctuaries of the Gulf of St. Lawrence, 1982–1988. Can. Field–Nat. 105: 60–66.

Chapdelaine, G., and P. Brousseau. 1992. Distribution, abundance, and changes of seabird populations of the Gaspe Peninsula, Québec, 1979 to 1989. Can. Field–Nat. 106: 427–434.

Chapdelaine, G., and J.–F. Rail. 1997. Relationship between cod fishery activities and the population of herring gulls on the north shore of the Gulf of St Lawrence, Québec, Canada. ICES J. Mar. Sci. 54: 708–713.

Chaput, G., and R.G. Bradford. 2003. American shad (*Alosa sapidissima*) in Atlantic Canada. DFO Can. Sci. Advis. Sec. Res. Doc. 2003/009.

Christensen, J.P., T.T. Packard, F.Q. Dortch, H.J. Minas, J.C. Gascard, C. Richez and P.C. Garfield. 1989. Carbon oxidation in the deep Mediterranean Sea: evidence for dissolved organic carbon source. Global Biogeochem. Cycles 3: 315–335.

Christian, J.R., A. Mathieu, D.H. Thomson, D. White and R.A. Buchanan. 2004. Effects of seismic energy on snow crab (*Chionoecetes opilio*). Environmental Studies Research Funds Report 144, 61 p.

Clark, C.W. 1994. Blue deep voice: insights from the Navy's Whale 93 program. Whalewatcher, 28: 6–11.

Comba, M.E., R.J. Norstrom, C.R. Macdonald and K.L.E. Kaiser. 1993. A Lake Ontario–Gulf of St. Lawrence dynamic mass budget for mirex. Environ. Sci. Technol. 27: 2198–2206.

Coote, A.R., and P.A. Yeats. 1979. Distribution of nutrients in the Gulf of St. Lawrence. Can. J. Fish. Aquat. Sci. 36: 122–131.

COSEPAC. 2001. Rapport du COSEPAC sur la situation de la tortue luth (*Dermochelys coriacea*) au Canada–Mise à jour. Comité sur la situation des espèces en péril au Canada. Ottawa. vii + 25 pp.

COSEPAC. 2003. Rapport du COSEPAC sur la situation de la morue franche (*Gadus morhua*) au Canada–Mise à jour. Comité sur la situation des espèces en péril au Canada. Ottawa. xi + 76 p.

Cossa, D. 1990. Chemical contaminants in the St. Lawrence Estuary and Saguenay Fjord. *In* Oceanography of a large–scale estuarine system, the St. Lawrence. *Edited by M.I. El–Sabh and N.S. Silververg.* Coastal and Estuarine Studies 39. Springer-Verlag, Berlin. pp. 239–268.

Cossa D., T.–T. Pham, B. Rondeau, B. Quémerais, S. Proulx and C. Surette. 1997. Bilan massif des contaminants chimiques dans le fleuve Saint–Laurent., Environnement Canada–Région du Québec, Conservation de l'environnement, Centre Saint–Laurent, Montreal.

Côté, J., S. Gravel, A. Méthot, A. Patoine, M. Roch and A. Staniforth. 1997a. The operational CMC/MRB Global Environmental Multiscale (GEM) model: Part I–Design considerations and formulation. Mon. Weather Rev. 126: 1373–1395.

Côté, J., S. Gravel, A. Méthot, A. Patoine, M. Roch and A. Staniforth. 1997b. The operational CMC/MRB Global Environmental Multiscale (GEM) model: Part II–Results. Monthly Weather Rev. 126: 1397–1418.

Couillard, C.M., P.V. Hodson and M. Castonguay. 1997. Correlations between pathological changes and chemical contamination in American eels, *Anguilla rostrata*, from the St. Lawrence River. Can. J. Fish. Aquat. Sci. 54: 1916–1927.

Couillard, D. 1982. Évaluation des teneurs en composés organochlorés dans le Fleuve, l'estuaire et le golfe Saint–Laurent, Canada. Environ. Pollut. 3: 239–270.

Couillard, C.M. 2002. A microscale test to measure petroleum oil toxicity to mummichog embryos. Environ. Toxicol. 17: 195-202.

Couillard, C.M. 2007. Effets toxiques des contaminants chez le béluga du Saint-Laurent. Compte rendu de l'atelier sur le béluga de l'estuaire du Saint-Laurent – Revue du programme des carcasses. *Édité par L. Mesure.* Sec. can. consult. sci. MPO, Compte rendu. 2007/005, pp. 23-27.

Couillard, C.M., B. Légaré et É. Pelletier. 2007. Évaluation des effets toxiques de l'ingestion de proies benthiques prélevées dans l'habitat du béluga du Saint-Laurent. Affiche présentée au 11e colloque annuel du Chapitre Saint-Laurent SETAC/SRA. Rimouski, QC. Mai 2007.

Couillard, C.M., I.I. Wirgin, M. Lebeuf, and B. Legare. 2004. Reduction of cytochrome P4501A with age in Atlantic tomcod from the St. Lawrence Estuary, Canada: relationship with emaciation and possible effect of contamination. Aquat.Toxicol. 68: 233-247.

Couillard, C.M., M. Lebeuf, M.G. Ikonomou, G.G. Poirier and W.J. Cretney. 2005. Low hepatic ethoxyresorufin-O-deethylase correlates with high organochlorine concentrations in Atlantic tomcod from the Atlantic east coast. Environ.Toxicol.Chem. 24: 2459-2469.

Cushing, D.H. 1988. The provident sea. Cambridge University Press, Cambridge. 329 p.

d'Anglejan, B. 1990. Recent sediments and sediment transport processes in the St. Lawrence Estuary. *In* Oceanography of a large–scale estuarine system, the St. Lawrence. *Edited by M.I. El–Sabh and N.S. Silververg.* Coastal and Estuarine Studies 39. Springer-Verlag, Berlin. pp. 109–129.

De Guise, S., A. Lagacé and P. Béland. 1994a. Tumors in St. Lawrence beluga whales (*Delphinapterus leucas*). Vet. Pathol. 31: 444–449.

De Guise, S., A. Lagacé and P. Béland. 1994b. True hermaphroditism in a St. Lawrence beluga whale (Delphinapterus leucas). Journal of Wildlife Diseases, 30(2), 287-290.

De Guise, S., D. Martineau, P. Béland and M. Fournier. 1995. Possible mechanisms of action of environmental contaminants on St. Lawrence beluga whales (*Delphinapterus leucas*). Environ. health persp. 4: 73-77.

De Guise, S., J. Bernier, D. Martineau, P. Béland and M. Fournier. 1996. Effects of in vitro exposure of beluga whale splenocytes and thymocytes to heavy metals. Environ. Toxic. Chem. 15(8): 1357-1364.

De Guise, S., D. Martineau, P. Béland and M. Fournier. 1998. Effects of in vitro exposure of beluga whale leukocytes to selected organochlorines. J. Toxic. Env. Health, Part A 55(7): 479-493.

de Lafontaine, Y., M.I. El–Sabh, M. Sinclair, S.N. Messieh and J.–D. Lambert. 1984a. Structure océanographique et distribution spatio–temporelle d'œufs et de larves de poissons dans l'estuaire maritime et la partie ouest du golfe Saint–Laurent. Sci. Tech. Eau 17: 43–50.

de Lafontaine, Y., M. Sinclair, M.I. El–Sabh, C. Lassus and R. Fournier. 1984b. Temporal occurrence of ichthyoplankton in relation to hydrographic and biological variables at a fixed station in the St. Lawrence estuary. Est. Coast. Shelf Sci. 18: 177–190.

de Lafontaine, Y., S. Demers and J. Runge. 1991. Pelagic food web interactions and productivity in the Gulf of St. Lawrence: A perspective. *In* The Gulf of St. Lawrence : small ocean or big estuary ? *Edited by J.-C. Therriault.* Publ. spéc. can. sci. halieut. aquat. 113: 99–123.

Descroix, A., M. Harvey, S. Roy and P.S. Galbraith. 2005. Macrozooplankton community patterns driven by water circulation in the St. Lawrence marine system, Canada. Mar. Ecol. Prog. Ser. 302: 103–119.

Desharnais, F., and N. Collison. 2001. Background noise levels in the area of the Gully, Laurentian Channel and Sable Bank. Rapport de client externe du CRDA 2001–028 préparé pour le ministère des Pêches et des Océans, 48 p.

Desrosiers, G., C. Savenkoff, M. Olivier, G. Stora, K. Juniper, A. Caron, L. Legendre, S. Mulsow, J. Grant, S. Roy, A. Grehan, P. Scaps, N. Silverberg, B. Klein, J.–É. Tremblay and J.–C. Theriault. 2000. Trophic structure of macrobenthos in the Gulf of St. Lawrence and on the Scotian Shelf. Deep–Sea Res. II 47(3–4): 663–697.

Desrosiers, J. 1994. Analyse photogrammétrique de la structure et de la dynamique de la population de bélugas du Saint–Laurent. Mémoire de M.Sc., Département de biologie. Université Laval, Québec.

DFO. 2000a. State of phytoplankton and zooplankton in the estuary and northwestern Gulf of St. Lawrence during 1999. DFO Science Stock Status Report C4–18. (2000).

DFO. 2000b. Northwest Atlantic harp seals. DFO Science Stock Status Report E1–01 (2000).

DFO 2001. Gaspereau Maritime Provinces Overview. DFO Science Stock Status Report D3-17.

DFO. 2002. 2001 State of the Ocean: chemical and biological oceanographic conditions in the Estuary and Gulf of St. Lawrence. DFO Science Stock Status Report G4–03 (2002).

Dionne, M., B. Sainte–Marie, E. Bourget and D. Gilbert. 2003. Distribution and habitat selection of early benthic stages of snow crab *Chionoecetes opilio*. Mar. Ecol. Prog. Ser. 259: 117–128.

Douglas, S.G., R.G. Bradford, and G. Chaput. 2003. Assessment of striped bass (*Morone saxatilis*) in the Maritime Provinces in the context of species at risk. DFO Can. Sci. Advis. Sec, Res. Doc. 2003/008.

Drapeau, G. 1980. Appreciation preliminaire de l'estuaire et du Golfe du Saint–Laurent dans le contexte des aménagements de bassins des principales rivières de la Côte Nord, Direction de l'environnement Hydro–Québec, INRS–Océanologie, Rimouski, 46 p.

Drinkwater, K.F. 2005. The response of Atlantic cod (*Gadus morhua*) to future climate change. ICES J. Mar. Sci. 62: 1327–1337.

Drinkwater, K.F., and D. Gilbert. 2004. Hydrographic variability in the waters of the Gulf of St. Lawrence, the Scotian Shelf and the eastern Gulf of Maine (NAFO Subarea 4) during 1991–2000. J. Northw. Atl. Fish. Sci. 34: 85–101.

Drinkwater, K., and P. Pépin. 2003. État de l'environnement physique et biologique. AZMP Bulletin PMZA 3: 3–7.

Drinkwater, K.F., E. Colbourne and D. Gilbert. 1995. Overview of environmental conditions in the northwest Atlantic in 1994. NAFO SCR Doc. 95/43.

Drolet, R., L. Fortier, D. Ponton and M. Gilbert. 1991. Production of fish larvae and their prey in subarctic southeastern Hudson Bay. Mar. Ecol. Prog. Ser. 77: 105–118.

Dutil, J.–D., M. Castonguay, D. Gilbert and D. Gascon. 1999. Growth, condition, and environmental relationships in Atlantic cod (*Gadus morhua*) in the northern Gulf of St. Lawrence and implications for management strategies in the northwest Atlantic. Can. J. Fish. Aquat. Sci. 56: 1818–1831.

Dutil, J.–D., J. Gauthier, Y. Lambert, A. Fréchet and D. Chabot. 2003. Cod stock rebuilding and fish bioenergetics: low productivity hypothesis. Can. Sci. Advis. Sec. Res. Doc. 2003/060.

El–Sabh, M.I. 1976. Surface circulation patterns in the Gulf of St. Lawrence. J. Fish. Res. Board Can. 33: 124–138.

El–Sabh, M.I. 1979. The lower St. Lawrence Estuary as a physical oceanographic system. Naturaliste canadien 106: 55–73.

El–Sabh, M.I., and N. Silverberg. 1990. The St. Lawrence Estuary: introduction. *In* Oceanography of a large–scale estuarine system, the St. Lawrence. *Edited by M.I. El–Sabh and N.S. Silververg.* Coastal and Estuarine Studies 39. Springer-Verlag, Berlin. pp. 1-9.

Engas, A., S. Lokkeborg, E. Ona and A.V. Soldal. 1996. Effects of seismic shooting on local abundance and catch rates of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*). Can. J. Fish. Aquat. Sci. 53(10): 2238–2249.

Ennis, G.P. 1995. Larval and postlarval ecology. *In* Biology of the lobster *Homarus americanus*. *Edited by J.R. Factor*. Academic Press Inc., San Diego. pp 23–46.

Environment Québec. 2004. Plantes menacées ou vulnérables au Québec. [online] Available from: http://www.menv.gouv.qc.ca/biodiversite/especes/# [accessed 22 décembre 2004].

Équipe de rétablissement du loup de mer. 2003. National recovery plan for the northern wolfish, *Anarhichas denticulatus*, and spotted wolfish, *Anarhichas minor*, in eastern Canadian waters. Plan national de rétablissement. Rétablissement des espèces canadiennes en péril (RESCAPE). Ottawa, Ontario. (document préliminaire, février 2004).

Fairchild, W.L., S.B. Brown and A. Moore. 2002. Effects of freshwater contaminants on marine survival in Atlantic salmon. *In* North Pacific Anadromous Fish Commission: Joint meeting on causes of marine mortality of salmon in the North Pacific and North Atlantic Oceans and in the Baltic Sea, Vancouver, BC, Canada, 12-15 March 2002. Technical Report 4: pp. 30-32.

Fairchild, W.L., E.O. Swansburg, J.T. Arsenault and S.B. Brown. 1999. Does an association between pesticide use and subsequent declines in catch of Atlantic salmon (*Salmo salar*) represent a case of endocrine disruption ? Environ.Health Perspect. 107: 349-358.

Farquharson, W.I. 1962. Tides, tidal streams and currents in the Gulf of St. Lawrence. Canadian Hydrographic Services, Department of Mines and Technical Surveys, Ottawa.

Fath, B.D. 2004. Distributed control in ecological networks. Ecol. Model. 179: 235–245.

Faucher, M., D. Caya, F.J. Saucier and R. Laprise. 2004. Sensitivity of the CRCM atmospheric and the Gulf of St. Lawrence ocean–ice models to each other. Atmosphere–Ocean 42(2): 85–100.

Fent, K. 1996. Ecotoxicology of organotin compounds. Crit. Rev. Toxicol. 26: 1–117.

Fent, K. 2006. Worldwide occurrence of organotins from antifouling paints and effects in the aquatic environment. *In* Handbook of Environmental Chemistry, Volume 5: Water Pollution, 5O: 71-100.

Fetzer, I., and H. Deubel. 2006. Effect of river run–off on the distribution of marine invertebrate larvae in the southern Kara Sea (Russian Arctic). J. Mar. Syst. 60: 98–114.

Fisher, A., D. Abler, E. Barron, R. Bord, R. Crane, D. DeWalle, C.G. Knight, R. Najjar, E. Nizeyimana, R. O'Connor, A. Rose, J. Shortle and B. Yarnal. 2000. Preparing for a changing climate–the potential consequences of climate variability and change–mid–Atlantic overview. Report of the Mid–Atlantic Regional Assessment. 68 p.

Fontaine, P.H. 1998. Whales of the north Atlantic: biology and ecology. Editions Multimondes, Québec, 290 p.

Forrester, W.D. 1974. Internal tides in the St. Lawrence estuary. J. Mar. Res. 32: 55–66.

Fortier, L., M. Levasseur, R. Drolet and J.–C. Therriault. 1992. Export production and the distribution of fish larvae and their prey in a coastal jet frontal region. Mar. Ecol. Prog. Ser. 85: 203–218.

Fortin, M.-G., C.M. Couillard, J. Pellerin, and M. Lebeuf. 2007. Effects of salinity on sublethal toxicity of atrazine to mummichog (*Fundulus heteroclitus*) larvae. Accepted for publication in Mar. Environ. Res.

Fournier, M., V. Degas, T. Colborn, F.O. Omara, F. Denizeau, E.F. Potworowski and P. Brousseau. 2000. Immunosuppression in mice fed on diets containing beluga whale blubber from the St Lawrence Estuary and the Arctic populations. Toxicol. Lett. 112: 1-3.

Fradette, P., and E. Bourget. 1980. Ecology of benthic epifauna of the Estuary and Gulf of St. Lawrence: factors influencing their distribution and abundance on buoys. Can. J. Fish. Aquat. Sci. 37(6): 979–999.

Fradette, P., et E. Bourget. 1981. Groupement et ordination appliqués à l'étude de la repartition de l'épifaune benthique de l'estuaire maritime et du golfe du Saint–Laurent. J. Exp. Mar. Biol. Ecol. 50(2–3): 133–152.

Frank, K.T., J.E. Carscadden and J.E. Simon. 1996. Recent excursions of capelin (*Mallotus villosus*) to the Scotian Shelf and Flemish Cap during anomalous hydrographic conditions. Can. J. Fish. Aquat. Sci. 53: 1473–1486.

Frank, K.T., B. Petrie, J.S. Choi and W.C. Leggett. 2005. Trophic cascades in a formerly cod–dominated ecosystem. Science 308: 1621–1623.

French B.L., W.L. Reichert, T. Hom, M. Nishimoto, H.R. Sanborn and J.E. Stein. 1996. Accumulation and dose–response of hepatic DNA adducts in English sole (*Pleuronectes vetulus*) exposed to a gradient of contaminated sediments. Aquat. Toxicol. 36: 1–16.

Gachon P., F.J. Saucier and R. Laprise. 2001. Atmosphere-ocean-ice interaction processes in the Gulf of St. Lawrence: numerical study with a coupled model. Sixth Conference on Polar Meteorology and Oceanography and the 11th Conference on Interaction of the Sea and Atmosphere, AMS (American Meteorological Society) meeting, San Diego (California, USA), 14-18 May 2001. Abstract volume, J1.18, J37-J40.

Gagné, F., C. Blaise, J. Pellerin, É. Pelletier, M. Douville, S. Gauthier-Clerc and L. Viglino. 2003. Sex alteration in soft-shell clams (*Mya arenaria*) in an intertidal zone of the St. Larence River (Quebec, Canada). Comp. Biochem. Physiol. 134C: 189-198.

Gagné, F., C. Blaise, J. Pellerin, É. Pelletier and J. Strand. 2006. Health status of *Mya arenaria* bivalves collected from contamianted sites in Canada (Saguenay fjord) and Denmark (Odense fjord) during their reproductive period. Ecotox.. Environ. Saf. 64: 348-361.

Gagnon, M., et M.I. El–Sabh. 1980. Effets de la marée interne et des oscillations de basses fréquences sur la circulation côtière dans l'estuaire du Saint–Laurent. Naturaliste canadien 107: 159–174.

Galbraith, P.S. 1992. Relating overturns to mixing and buoyancy flux. Ph.D. thesis, Dalhousie University, Halifax, NS, 243 p.

Galbraith, P.S. 2006. Winter water masses in the Gulf of St. Lawrence. J. Geophys. Res. C: Oceans 111(6), C06022, doi: 10.1029/2005 JCØØ3159.

Galbraith, P.S., F.J. Saucier, N. Michaud, D. Lefaivre, R. Corriveau, F. Roy, R. Pigeon and S. Cantin. 2002. Shipborne monitoring of near–surface temperature and salinity in the Estuary and Gulf of St. Lawrence. AZMP Bulletin PMZA 2: 26–30.

Gan, J., R.G. Ingram and R. Greatbatch. 1997. On the unsteady separation/intrusion of the Gaspé current and variability in Baie–des–Chaleurs, modelling studies. J Geophys. Res 102: 15567–15581.

Gauthier, J. M., H. Dubeau and E. Rassart. 1998. Mercury-induced micronuclei in skin fibroblasts of beluga whales. Environ. Toxicol. Chem. 17(12): 2487-2493.

Gauthier-Clerc, S., J. Pellerin, C Blaise and F. Gagné. 2002. Delayed gametogenesis of *Mya arenaria* in the Saguenay fjord (Canada): a consequence of endocrine disruptors ? Comp. Bioch. Physiol. Part C 131(4): 457-467.

Gendron, A., N. Silverberg, B. Sundby and J. Lebel. 1986. Early diagenesis of cadmium and cobalt in Laurentian Trough sediments. Geochim. Cosmochim. Acta 50: 741–747.

Gibson, M. 2003. Seashores of the Maritimes. Nimbus Publishing Ltd., Halifax, N.S. 346 p.

GIEC. 2001:Climate change 2001: impacts, adaptation, and vulnerability. Contribution of working group 2 to the third assessment report of the intergovernmental panel on climate change. *Edited by McCarthy J.J., Canziani O.F., Leary N.A., Dokken D.J. and White K.S.* Cambridge University Press. Cambridge R.-U., and New York USA. 1032 p. (en anglais seulement).

Gilbert, D. 2004. Propagation of temperature signals from the northwest Atlantic continental shelf edge into the Laurentian Channel. ICES CM 2004/N: 07, 12 p.

Gilbert, D., and B. Pettigrew. 1993. Current–meter data from Bonne Bay, Newfoundland, during the summer of 1991, Can. Data Rep. Hydrogr. Ocean Sci. 122: 63 pp.

Gilbert, D., and B. Pettigrew. 1997. Interannual variability (1948–1994) of the CIL core temperature in the Gulf of St. Lawrence. Can. J. Fish. Aquat. Sci. 54 (Suppl. 1): 57–67.

Gilbert, M., L. Fortier, D. Ponton and R. Drolet. 1992. Feeding ecology of marine fish larvae across the Great Whale River plume in seasonally ice–covered southeastern Hudson Bay. Mar. Ecol. Prog. Ser. 84: 19–30.

Gilbert, D., A.F. Vézina, B. Pettigrew, D.P. Swain, P.S. Galbraith, L. Devine et N. Roy. 1997. État du golfe du Saint–Laurent: conditions océanographiques en 1995. Rapp. tech. can. hydrogr. sci. océan 191: xii + 113 p.

Gilbert, D., B. Sundby, C. Gobeil, A. Mucci, and G.–H. Tremblay 2005. A seventy–two–year record of diminishing deep–water oxygen in the St. Lawrence Estuary: the northwest Atlantic connection. Limnol. Oceanogr. 50(5): 1654–1666.

Gilbert, M., R. Alexander, J. Arsenault, W.R. Ernst, W. Fairchild, P. Hennigar, G. Julien, T. King, M. Lebeuf et D. Lefaivre. 1998. Contamination par les BPC des sédiments et du crabe des neiges (*Chionoecetes opilio*) aux environs du site du naufrage de la barge *Irving Whale* après son renflouage. Rapp. tech. can. sci. halieut. aquat. 2204: x+32 pp.

Gobeil, C. 1991. Inventaire de la contamination des sédiments du chenal Laurentien: données sur les métaux et les éléments nutritifs. Rapp. stat. can. sci. halieut. aquat. 854: iv+63 pp.

Gobeil, C., et M. Lebeuf. 1992. Inventaire de la contamination des sédiments du Chenal Laurentien: les biphényles polychlorés. Rapp. tech. can. sci. halieut. aquat. 1851: 45 pp.

Gobeil, C., B. Sundby and N. Silverberg. 1981. Factors influencing particulate matter geochemistry in the St. Lawrence estuary turbidity maximum. Mar. Chem. 10: 123–140.

Gobeil, C., D. Cossa et J. Piuze. 1983. Distribution des concentrations en mercure dans les eaux de l'estuaire moyen du Saint–Laurent. Rapp. tech. can. hydrogr. sci. océan. 17: 14 p.

Gobeil, C., N. Silverberg, B. Sundby and D. Cossa. 1987. Cadmium diagenesis in Laurential Through sediments. Geochim. Cosmochim. Acta 51: 589–596.

Gobeil, C., Y. Clermont et G. Paquette. 1997. Concentrations en mercure, plomb et cadmium chez diverses espèces de poissons de fond, de poissons pélagiques et de crustacés de l'estuaire et du golfe du Saint–Laurent et du fjord du Saguenay. Rapp. stat. can. sci. halieut. aquat. 1011, 88 pp.

Godin, G. 1979. La marée dans le golfe et l'estuaire du Saint–Laurent. Naturaliste canadien 106: 105–121.

Gordon, D.C., K.D. Gilkinson, E.L.R. Kenchington, J. Prena, C. Bourbonnais, K. MacIsaac, D.L. McKeown and W.P. Vass. 2002. Summary of the Grand Banks otter trawling experiment (1993–1995): effects on benthic habitat and communities. Can. Tech. Rep. Fish. Aquat. Sci. No 2416.

Gosselin, J.–F., V. Lesage and A. Robillard. 2001. Population index estimate for the beluga of the St. Lawrence River Estuary in 2000. DFO Can. Sci. Advis. Res. Doc. 2001/049, 21 pp.

Gratton, Y., G. Mertz and J.A. Gagné. 1988. Satellite observations of tidal upwelling and mixing in the St. Lawrence Estuary. J. Geophys. Res. 93: 6947–6954.

Grégoire, F., D. Chabot, C. Savenkoff, C. Lévesque, J. Guérin, J. Hudon and J. Lavers. 2003. Capelin (*Mallotus villosus*) fishery, biology and distribution in NAFO Divisions 4RST in 2002. DFO Can. Sci. Advis. Sec. Res. Doc. 2003/083, 68 p.

Grégoire, F., W. Barry and J. Barry. 2006. West coast of Newfoundland capelin (*Mallotus villosus* M.) and Atlantic herring (*Clupea harengus harengus* L.) larval survey, part 2: Abundance estimates and marine community analyses of the data collected in partnership with the industry (Barry Group) in July 2004. Can. Tech. Rep. Fish. Aquat. Sci. 2650: viii + 51 p.

Guillemart, C. 2006. L'accumulation du cadmium chez le pétoncle géant (*Placopecten magellanicus*) et le pétoncle d'islande (*Chlamys islandica*) de la Côte Nord (Québec) et dans leur environnement. Mémoire de maîtrise ès Sciences, département d'océanographie, UQAR, Rimouski, QC.

Hammill, M.O., and G.B. Stenson. 1997. Estimated prey consumption by harp seals (*Phoca groenlandica*), grey seals (*Halichoerus grypus*), harbour seals (*Phoca vitulina*) and hooded seals (*Cystophora cristata*) in the Northwest Atlantic. NAFO SCR Doc. 97/40.

Han, G., P. Roussel and J.W. Loder. 2002. Seasonal–mean circulation and tidal currents in the Gully. *In* Advance in understanding the Gully ecosystem: a summary of research projects conducted at the Bedford Institut of Oceanography (1999–2001). *Edited by D.C. Gordon and D.G. Fenton*. Can. Tech. Rep. Fish. Aquat. Sci. 2377: 39–48.

Hanson, J.M., and M. Lanteigne. 2000. Evaluation of Atlantic cod predation on American lobster in the southern Gulf of St. Lawrence, with comments on other potential fish predators. Trans. Am. Fish. Soc. 129(1): 13–29.

Hargrave, B.T., G.C. Harding, K.F. Drinkwater, T.C. Lambert and W.G. Harrison. 1985. Dynamics of the pelagic food web in St. Georges Bay, southern Gulf of St. Lawrence. Mar. Ecol. Prog. Ser. 20(3): 221–240.

Harvey, M., and M. Starr. 2005. 2003 state of the ocean: chemical and biological oceanographic conditions in the Estuary and Gulf of St. Lawrence. DFO, DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2005/053, 20 p.

Harvey, M., J.–F. St–Pierre, P. Joly and G. Morrier. 2002. Oceanographic conditions in the Estuary and the Gulf of St. Lawrence in 2001: zooplankton. . DFO Can. Sci. Advis. Sec. Res. Doc. 2002/046.

Harvey, M., J.-F. St-Pierre, A. Gagné, M.F. Beaulieu et Y. Gagnon. 2003. Oceanographic conditions in the Estuary and the Gulf of St. Lawrence during 2002: zooplankton. DFO DFO Can. Sci. Advis. Sec. Res. Doc. 2003/077: 22 pp.

Harvey, M., J.–F. St–Pierre, L. Devine, A. Gagné, Y. Gagnon and M.–F. Beaulieu. 2004. Oceanographic conditions in the Estuary and the Gulf of St. Lawrence during 2003: zooplankton. DFO Can. Sci. Advis. Sec. Res. Doc. 2004/080, 31 p.

Hassan, E.M. 1975. Some effects of river regulation on marginal seas. Ocean Management 2: 333–344.

Hatin, D., et F. Caron. 2002. Déplacements et caractéristiques des esturgeons noirs (*Acipenser oxyrinchus*) adultes dans l'estuaire du fleuve Saint-Laurent en 1998 et 1999. Société de la faune et des parcs du Québec, Direction de la recherche sur la faune. 151 p.

Henry, E., and M.O. Hammill. 2001. Impact of small boats on the haulout activity of harbour seals (*Phoca vitulina*) in Metis Bay, Saint–Lawrence Estuary, Québec, Canada. Aquat. Mamm. 27(2): 140–148.

Hodson, P.V., M. Castonguay, C.M. Couillard, C. Desjardins, É. Pelletier and R. McLeod. 1994. Spatial and temporal variations in chemical contamination of american eels (*Anguilla rostrata*) captured in the estuary of the St. Lawrence river. Can. J. Fish. Aquat. Sci. 51: 464-478.

Humborg, C., V. Ittekkot, A. Cociasu and B.V. Bodungen. 1997. Effect of Danube River dam on Black Sea biogeochemistry and ecosystem structure. Nature 386: 385–388.

Hunt, H.L. 2004. Effects of epibenthic predators in flow: transport and mortality of juveniles of the soft shell clam *Mya arenaria*. Mar. Ecol. Prog. Ser. 279: 151–160.

Hunter, M.D., and P.W. Price. 1992. Playing chutes and ladders: heterogeneity and the relative roles of bottom–up and top–down forces in natural communities. Ecology 73: 724–732.

Hutching, J.A., T.D. Bishop and C.R. McGregor–Shaw. 1999. Spawning behaviour of Atlantic cod, *Gadus morhua*: evidence of mate competition and mate choice in a broadcast spawner. Can. J. Fish. Aquat. Sci. 56: 97–107.

Ingram, R.G. 1975. Influence of tidal–induced vertical mixing on primary productivity in the St. Lawrence Estuary. Mémoires Société Royale de Liège, 6ième série, tome VII: 59–74.

Ingram, R.G. 1976. Characteristics of a tide–induced estuarine front. J. Geophys. Res. 81: 1951–1959.

Ingram, R.G. 1983. Vertical mixing at the head of the Laurentian Channel. Estuar. Coast. Shelf Sci. 16: 333–338.

Ingram, R.G. 1985. Frontal characteristics at the head of the Laurentian Channel. Naturaliste canadien 112: 31–38.

IPCC 2001: Climate change 2001: the scientific basis. Contribution of working group 1 to the third assessment report of the intergovernmental panel on climate change. *Edited by Houghton J.T., Ding Y., Griggs D.J., Noguer M., Van der Linden P.J., Dai X., Maskell K., and Johnson C.A.* Cambridge University Press, Cambridge UK and New York USA. 881 p. (in English only).

Jackson, J.B.C., M.X. Kirby, W.H. Berger, K.A. Bjorndal, L.W. Botsford, B.J. Bourque, R.H. Bradbury, R. Cooke, J. Erlandson, J.A. Estes, T.P. Hughes, S. Kidwell, C.B. Lange, H.S. Lenihan, J.M. Pandolfi, C.H. Peterson, R.S. Steneck, M.J. Tegner and R.R. Warner. 2001. Historical overfishing and the recent collapse of coastal ecosystems. Science 293: 629–638.

Jennings, S., and M.J. Kaiser. 1998. The effects of fishing on marine ecosystems. Advis. Mar. Biol. 34: 201–352.

Johannessen, O.M., K. Khvorostovsky, M.W. Miles and L.P. Bobylev. 2005. Recent ice–sheet growth in the interior of Greenland. Science 310: 1013–1016.

Kennedy, K.M., and R.J. Benson. 1993. Report of heavy metal analysis conducted on mussel (*Mytilus edulis*) samples collected at 55 sites in Newfoundland. Can. Tech. Rep. Fish. Aquat. Sci. 1937: iii, 17 p.

Kimmerer, W. J. 2002. Effects of freshwater flow on abundance of estuarine organisms: physical effects or trophic linkages. Mar. Ecol. Prog. Ser. 243: 39–55.

Kingsley, M.C.S., and R.R. Reeves. 1998. Aerial surveys of cetaceans in the Gulf of St. Lawrence in 1995 and 1996. Can. J. Zool. 8: 1529–1550.

Koutitonsky, V.G., and G.L. Bugden. 1991. The physical oceanography of the Gulf of St. Lawrence: a review with emphasis on the synoptic variability of the motion. *In* The Gulf of St. Lawrence : small ocean or big estuary? *Edited by J.-C. Therriault.* Publ. spéc. can. sci. halieut. aquat. 113: 57–90.

Labat, D., Y. Godderis, J.L. Probst and J.L. Guyot. 2004. Evidence for global runoff increase related to climate warming. Advis.Water Res. 27: 631–642.

Lacroix, A., M. Fournier, M. Lebeuf, J.J. Nagler and D.G. Cyr. 2001. Pahogocytic response of macrophage from the pronephros of American plaice (*Hipoglossoides platessoides*) exposed to contaminated sediments from Baie des Anglais, Quebec. Chemosphere 45: 599-607.

Lapierre, P., S. De Guise, D.C. Muir, R. Norstrom, P. Béland and M. Fournier. 1999. Immune functions in the Fisher rat fed Beluga whale (*Delphinapterus leucas*) blubber from the contaminated St. Lawrence estuary. Environ. Res. 80(2): S104-S112.

Larkin, P.A. 1996. Concepts and issues in marine ecosystem management. Rev. Fish. Biol. 6: 139–164.

Larouche, P. 1998. SeaWiFS validation program in the St. Lawrence Estuary and Gulf. Proceedings of the Fifth International Conference on Remote Sensing for Marine and Coastal Environments, San Diego, California, 5–7 October 1998, pp. I349–I359.

Larouche, P. 2000. Results from the 2nd St. Lawrence Estuary and Gulf SeaWiFS validation cruise. Proceedings of the Sixth International Conference of Remote Sensing for Marine and Coastal Environments, Charleston, South Carolina, 1–3 May 2000, pp. I351–I358.

Lauzier, L.M., and W.B. Bailey. 1957. Features of the deep waters of the Gulf of St. Lawrence. Bull. Fish. Res. Board Can. 111: 213–250.

Lauzier, L.M., and R.W. Trites. 1958. The deep waters of the Laurentian Channel.. J. Fish. Res. Board Can. 15: 1247–1257.

Law, R., J. Hurstwayte and D. Sims. 2003. Monitoring of the quality of the marine environment, 2000–2001. Centre for environment, fisheries and aquaculture science (Lowestoft, U.K.) Aquat. Env. Monit. Rep. 56, 37 p.

Lawson, J., and I. McQuinn. 2004. Review of the potential hydrophysical–related issues in Canada, risks to marine mammals, and monitoring and mitigation strategies for seismic activities. DFO Can. Sci. Advis. Sec. Res. Doc. 2004/121, 57 p.

Leatherwood, S., D.K. Caldwell and H.E. Winn. 1976. Whales, dolphins and porpoises of the western North Atlantic: a guide to their identification. NOAA Tech. Rep. NMFS Circular 396.

Lebeuf, M., Y. St–Pierre, Y. Clermont et C. Gobeil. 1999. Concentrations de biphényles polychlorés (BPC) et de pesticides organochlorés chez trois espèces de poissons de fond de l'estuaire et du golfe du Saint–Laurent et du fjord du Saguenay. Rapp. stat. can. sci. halieut. aquat. 1059, 108 p.

Lebeuf, M., B. Gouteux, L. Measures and S. Trottier. 2004a. Levels and temporal trends (1988–1999) of polybrominated diphenyl ethers in beluga whales (*Delphinapterus leucas*) from the St. Lawrence Estuary, Canada. Environ. Sci. Technol. 38(11): 2971–2977.

Lebeuf, M., C.M. Couillard, B. Légaré and S. Trottier. 2006. Effects of DeBDE and PCB-126 on hepatic concentrations of PBDEs and methoxy-PBDEs in Atlantic tomcod. Environ. Science Technol. 40: 3211-3216.

Lebeuf, M., M. Noël, S. Trottier, and L. Measures. 2007. Temporal trends (1987-2002) of persistent, bioaccumulative and toxic (PBT) chemicals in beluga whales (*Delphinapterus leucas)* from the St. Lawrence Estuary, Canada. Sci, Tot. Env. 383: 216-231.

Lebeuf , M., C. M. Couillard , R. L. Roy , C. DeBlois, S. Trottier, M. Noël, A. Ouellet and G. Allard. 2004b. Concentrations of pesticides in water samples from St Lawrence Estuary tributaries. Proceedings of the 31st Aquatic Toxicity Workshop, Charlottetown, PEI, Canada. *Edited by L.E. Burridge, K. Haya and A.J. Niimi*. Can. Tech. Rep. Fish. Aquat. Sci. 2562.

Leblanc, C.H., and G.J. Chaput. 1991. Landings of estuarine fishes in the Gulf of St. Lawrence 1917–1988. Can. Data Rep. Fish. Aquat. Sci. 842, 101 p.

Lee, K., J.J. Nagler, M. Fournier, M. Lebeuf and D.G. Cyr. 1999. Toxicological characterization of sediments from Baie des Anglais on the St. Lawrence Estuary. Chemosphere 39: 1019–1035.

Lefebvre, L., and J.–C. Brêthes. 1991. Influence of growth and environmental factors on the feeding of snow crabs, *Chionoecetes opilio* (O. Fabricius), in the southwest of the Gulf of St. Lawrence. Can. J. Zool. 69 (2): 489–494.

Lefèvre, D., M. Denis, C.E. Lambert and J.–C. Miquel. 1996. Is DOC the main source of organic remineralization in the ocean water column? J. Mar. Syst. 7: 281–291.

Le Fouest, V., B. Zakardjian, F.J. Saucier and M. Starr. 2005. Seasonal versus synoptic variability in planktonic production in a high–latitude marginal sea: the Gulf of St. Lawrence (Canada). J. Geophys. Res. 110(9): 1–21.

LEP (*Loi sur les espèces en péril*). 2005. « liste des espèces ». [En ligne : 7 janvier 2005] < http://www.sararegistry.gc.ca/species/default_f.cfm> (page Web consultée le 7 janvier 2005).

Lesage, V., and M. Kingsley. 1998. Updated status of the St. Lawrence River population of the beluga, *Delphinapterus leucas*. Can. Field–Nat. 112(1): 98–114.

Lesage, V., C. Barrette, M.C.S. Kingsley and B. Sjare. 1999. The effects of vessel noise on the vocal behaviour of belugas in the St. Lawrence River Estuary, Canada. Mar. Mamm. Sci. 15(1): 65–84.

Lesage, V., M.O. Hammill and K.M. Kovacs. 2001. Marine mammals and the community structure of the Estuary and Gulf of St. Lawrence, Canada: evidence from stable isotope analysis. Mar. Ecol. Prog. Ser. 210: 203–221.

Levasseur, M., J.–C. Therriault and L. Legendre. 1984. Hierarchical control of phytoplankton succession by physical factors. Mar. Ecol. Prog. Ser. 19: 211–222.

Levasseur, M., L. Fortier, J.-C. Therriault and P. Harrison. 1992. Phytoplankton dynamics in a coastal jet frontal region. Mar. Ecol. Progr. Ser. 86: 283-295.

Link, J.S., and L.P. Garrison. 2002. Changes in piscivory associated with fishing induced changes to the finfish community on Georges Bank. Fish. Res. 55: 71–86.

Lock, A.R., R.G.B. Brown and S.H. Gerriets. 1994. Gazetteer of marine birds in Atlantic Canada–an atlas of seabird vulnerability to oil pollution. Canadian Wildlife Service, Atlantic region. 137 p.

Locke, A. 2002. The ichthyoplankton and invertebrate zooplankton of the coastal waters of Cape Breton Island: a review. Can. Manuscr. Rep. Fish. Aquat. Sci. 2606. 24 p.

Louchouarn, P., M. Lucotte, R. Canuel, J.–P. Gagné and L.–F. Richard. 1997. Sources and early diagenesis of lignin and bulk organic matter in the sediments of the Lower St. Lawrence Estuary and the Saguenay Fjord. Mar. Chem. 58 (1–2): 3–26.

Lu, Y., K. Thompson and D.G. Wright. 2002. Tidal currents and mixing in the Gulf of St. Lawrence: an application of the incremental approach to data assimilation. Can. J. Fish. Aquat. Sci. 58: 723–735.

Maguire, R.J. 1992. Environmental assessment of tributyltin in Canada. Water Sci. Technol. 25: 125–132.

Maillot, J., R. Sarrazin, B. Bilodeau, N. Brunet and P. Pellerin. 1997. Development of the 35 km version of the operational regional forecast system, Atmosphere–Ocean. 35: 1–28.

Mamelona, J., and E. Pelletier. 2003. Butyltins biomagnification from macroalgae to green sea urchins: a field assessment. App. Organometallic Chem. 17: 759–766.

Mance, G. 1987. Pollution threat of heavy metals in aquatic environments. Elsevier B.V., 372 p.

Mark, S., L. Provencher et J. Munro. 2003. Approche pour l'évaluation et le suivi de la santé de l'écosystème avec application à la communauté à *Mya–Macoma*. Rapp. tech. can. sci. halieut. aquat. 2491: ix + 85 p.

Marsden, R.F., and Y. Gratton. 1998. Surface pulses in the Lower St. Lawrence Estuary. Atmosphere–Ocean 36 (3): 271–295.

Martineau, D., A. Lagacé, P. Béland, R. Higgins, D. Armstrong and L. R. Shugart. 1988. Pathology of stranded beluga whales (*Delphinapterus leucas*) from the St. Lawrence Estuary, Québec, Canada. J. Comp. Path. 98: 287-311.

Martineau, D., K. Lemberger, A. Dallaire, P. Labelle, T.P. Lipscomb, P. Michel and I. Mikaelian. 2002. Cancer in wildlife, a case study: beluga from the St. Lawrence estuary, Québec, Canada. Environ. Health Perspect. 110(3): 285–92.

Massad, R., and P. Brunel. 1979. Associations by station, density and diversity of polychaetes of the circa–littoral and deep benthos of the seaward part of the St. Lawrence Estuary. Naturaliste canadien 106(1): 229–253.

McAllister, B.G., and D.E. Kime. 2004. Early life exposure to environmental levels of the aromatase inhibitor tributyltin causes masculinisation and irreversible sperm damage in zebrafish (*Danio rerio*). Aquat Toxicol. 65: 309-316.

McCauley, R.D., J. Fewtrell, A.J. Duncan and A. Adhitya. 1998. Behavioural, physiological and pathological response of fishes to air gun noise. Bioacoustics 12(2): 318–321.

McCauley, R.D., J. Fewtrell and A.N. Popper. 2003. High intensity anthropogenic sound damages fish ears. J. Acoust. Soc. Am. 113(1): 638–642.

McDowall, R.B. 1987. The occurrence and distribution of diadromy among fishes. Am. Fish. Soc. Symp. 1: 1–13.

McKinney, M.A., S. De Guise, D. Martineau, P. Béland, M. Lebeuf, and R.J. Letcher. 2006. Organohalogen contaminants and metabolites in beluga whale (*Delphinapterus leucas*) liver from two Canadian populations. Environ. Toxicol. Chem. 25: 1246-1257.

McLellan, H.J. 1957. On the distinctness and origin of the slope water off the Scotian Shelf and its easterly flow south of the Grand Banks. J. Fish. Res. Board. Can. 14: 213–239.

McRuer, J., T. Hurlbut and B. Morin. 2000. Status of Atlantic wolffish (*Anarhichas lupus*) in the Maritimes (NAFO Sub–Area 4 and Division 5Ze). DFO Can. Stock Assess. Sec. Res. Doc. 2000/138.

Medcof, J.C. 1968. Oyster farming in the Maritimes. Bull. Fish. Res. Board Can. 131, 178 p.

Mertz, G., and M.I. El–Sabh. 1989. An autumn instability event in the Gaspe Current. J. Phys. Oceanogr. 19(1): 148–156.

Mertz, G., V.G. Koutitonsky and Y. Gratton. 1991. On the seasonal cycle of the Gaspé Current. *In* The Gulf of St. Lawrence : small ocean or big estuary? *Edited by J.-C. Therriault*. Publ. spéc. can. sci. halieut. aquat. 113: 149–152.

Michaud, M.-H., and E. Pelletier. 2006. Sources and fate of butyltins in the St. Lawrence Estuary ecosystem. Chemosphere 64(7): 1074-1082.

Michaud, R. 1993. Distribution estivale du béluga du Saint–Laurent ; synthèse 1986 à 1992. Rapp. tech. can. sci. halieut. aquat. 1906: vi + 28 p.

Michaud, R., et J. Giard. 1998. Les rorquals communs et les activités d'observation en mer dans l'estuaire maritime du Saint–Laurent entre 1994 et 1996. 2) Évaluation de l'impact des activités d'observation en mer sur le comportement des rorquals communs. Rapport final, GREMM, Tadoussac, QC: 24 pp.

Milliman, J.D. 1997. Blessed dams or damned dams? Nature 386: 325–326.

Muir, D., K. Koczanski, B. Rosenberg and P. Béland. 1990. Persistent organochlorines in beluga whales (*Delphinapterus leucas*) from the St. Lawrence River Estuary. 2. Temporal trends, 1982–1994. Environ. Pollut. 93(2): 235–245.

Nelson, M.M., B.J. Crear, P.D. Nichols and D.A. Ritz. 2003. Feeding southern rock lobster, *Jasus edwardsii* Hutton, 1875, phyllosomata in culture: recent progress with lipid–enriched Artemia. http://www.scopus.com/scopus/source/sourceInfo.url?sourceId=22586J. Shellfish Res. 22(1): 225–233.

Neu, H.J.A. 1982a. Man–made storage of water–resources – a liability to the ocean environment 1. Mar. Pollut. Bull. 13: 7–12.

Neu, H.J.A. 1982b. Man–made storage of water–resources – a liability to the ocean environment 2. Mar. Pollut. Bull. 13: 44–47.

Nozères, C., M. Bérubé, V. Haeberle, R. Miller and F. Proust. 2003. Marine species identification guide for the St. Lawrence. Maurice Lamontagne Institute, Department of Fisheries and Oceans [online]. Available at http://www.osl.gc.ca/guide_sp/en/index.html [accessed 7 June 2003].

O'Connell, M.F., D.G. Reddin, P.G. Amiro, F. Caron, T.L. Marshall, G. Chaput, C.C. Mullins, A. Locke, S.F. O'Neil and D.K. Cairns. 1997. Estimates of conservation spawner requirements for Atlantic salmon (*Salmo salar L.*) for Canada. DFO Can. Sec. Advis. Sci. Res. Doc. 97/100.

Ouellet, P., and D. Lefaivre. 1994. Vertical distribution of shrimp (*Pandalus borealis*) larvae in the Gulf of St Lawrence: implications for trophic interactions and transport. Can. J. Fish. Aquat. Sci. 51: 123–132.

Ouellet, P., D. Lefaivre and V. Koutitonsky. 1990. Distribution of shrimp (*Pandalus borealis*) larvae and hydrographic pattern in the northern Gulf of St. Lawrence. Can. J. Fish. Aquat. Sci. 47: 2068–2078.

Ouellet, P., J.–P. Allard et J.–F. St–Pierre. 1994. Distribution des larves d'invertébrés décapodes (Pandalidae, Majidae) et des œufs et larves de poissons dans le nord du golfe du Saint–Laurent en mai et juin de 1985 à 1987 et 1991–1992. Rapp. tech can. sci. halieut. aquat. 2019: viii+60 p.

Ouellet, P., Y. Lambert and M. Castonguay. 1997. Spawning of Atlantic cod (*Gadus morhua* L.) in the Northern Gulf of St Lawrence: a study of egg and adult distributions and characteristics. Can. J. Fish. Aquat. Sci. 54: 198–210.

Pace, M.L., J.J. Cole, S.R. Carpenter and J.F. Kitchell. 1999. Trophic cascades revealed in diverse ecosystems. Trends Ecol. Evol. 14: 483–488.

Packard, T., W. Chen, D. Blasco, C. Savenkoff, A.F. Vézina, R. Tian., L. St.–Amand, S.O. Roy, C. Lovejoy, B. Klein, J.–C. Therriault, L. Legendre and R.G. Ingram. 2000. Dissolved organic carbon in the Gulf of St. Lawrence. Deep–Sea Res. Part II 47: 435–459.

Paille, N., J. Lambert, N. Simard et S. Pereira. 2006. Le crabe vert (*Carcinus maenas*): revue de littérature et situation aux Îles–de–la–Madeleine. Rapp. can. ind. sci. halieut. aquat. 276: vi + 36 p.

Painchaud, J., and J.–C. Therriault. 1985. Heterotrophic potential in the St. Lawrence Estuary: distribution and controlling factors. Naturaliste canadien 112: 65–76.

Painchaud, J., and J.–C. Therriault. 1989. Relationships between bacteria, phytoplankton and particulate organic carbon in the upper St. Lawrence estuary. Mar. Ecol. Prog. Ser. 56: 301–311.

Painchaud, J., D. Lefaivre and J.–C. Therriault. 1987. Box model analysis of bacterial fluxes in the St. Lawrence estuary. Mar. Ecol. Prog. Ser. 41: 241–252.

Painchaud, J., D. Lefaivre, J.–C. Therriault and L. Legendre. 1995. Physical processes controlling bacterial distribution and variability in the upper St. Lawrence estuary. Estuaries 18: 433–444.

Painchaud, J., D. Lefaivre, J.–C. Therriault and L. Legendre. 1996. Bacterial dynamics in the upper St. Lawrence estuary. Limnol. Oceanogr. 41: 1610–1618.

Parkinson, C.L. 2000. Variability of Arctic sea ice: the view from space, an 18–year record. Arctic 53(4): 341–358.

Parsons, D.G., and J. Fréchettte. 1989. Fisheries for northern shrimp (*Pandalus borealis*) in the northwest Atlantic from Greenland to the Gulf of Maine. *In* Marine invertebrate fisheries: their assessment and management. *Edited by J.F. Caddy*, John Wiley and Sons, New-York. pp. 63–85.

Pellerin, P., H. Ritchie, F. Saucier, F. Roy S. Desjardins, M. Valin and V. Lee. 2004. Impact of a two way coupling between an atmospheric and an ocean–ice model over the Gulf of St. Lawrence. Month. Weath. Rev. 132(6): 1379–1398.

Pelletier, E., and C. Normandeau.1997. Distribution of butyltin residues in mussels and sea stars of the St. Lawrence Estuary. Environ. Technol. 18: 1203–1208.

Pelletier, E., G. Canuel, J. Padros, Y. Clermont et C. Gobeil. 1999. Concentrations d'hydrocarbures aromatiques polycycliques chez quatre espèces de poissons de fond et deux espèces de crustacés de l'estuaire et du golfe du Saint–Laurent et du fjord du Saguenay. Rapp. stat. can. sci. halieut. aquat. 1052, v + 20 p.

Petrie, B., and K. Drinkwater. 1993. Temperature and salinity variability on the Scotian shelf and in the Gulf of Maine 1945–1990. J. Geophys. Res. 98(C11): 20079–20089.

Petrie, B., and P.A. Yeats. 2000. Annual and interannual variability of nutrients and their estimated fluxes in the Scotian Shelf – Gulf of Maine region. Can. J. Fish. Aquat. Sci. 57: 2536–2546.

Petrie, B., B. Toulany and C.J.R. Garrett. 1998. The transport of water, heat and salt through the Strait of Belle Isle. Atmosphere–Ocean 26: 234–251.

Pingree, R.D., and D.K. Griffiths. 1980. A numerical model of the M2 tide in the Gulf of St. Lawrence. Oceanol. Acta 3: 221–225.

Pippard, L. 1985. Patterns of movement of the St. Lawrence white whales. Prepared for the Canadian Wildlife Service and Parks Canada. Final report. 500 p.

Plante, S., D. Chabot and J.D. Dutil. 1998. Hypoxia tolerance in Atlantic cod. J. Fish. Biol. 53(6): 1259–1284.

Plourde, J., and J.–C. Therriault. 2004. Climate variability and vertical advection of nitrates in the Gulf of St. Lawrence, Canada. Mar. Ecol. Prog. Ser. 279: 33–43.

Plourde, S., and M. Castonguay. 2005. The RIVSUM – zooplankton biomass – Atlantic mackerel story: does it hold with a second decade of data? Poster E16, GLOBEC Symposium "Climate Variability and Sub–Arctic Marine Ecosystems," Victoria, B.C., Canada, 16–20 May 2005.

Plourde, S., and J.A. Runge. 1993. Reproduction of the planktonic copepod *Calanus finmarchicus* in the lower St. Lawrence Estuary: relation to the cycle of phytoplankton production and evidence for a *Calanus* pump. Mar. Ecol. Prog. Ser 102: 217–227.

Plourde, S., P. Joly, J.A. Runge, B. Zarkardjian and J. Dodson. 2001. Life cycle of *Calanus finmarchicus* in the lower St. Lawrence Estuary: the imprint of circulation and late timing of the spring phytoplankton bloom. Can. J. Fish. Aquat. Sci. 58: 647–658.

Plourde, S., J. Dodson, J.A. Runge and J.–C. Therriault. 2002. Spatial and temporal variations in copepod community structure in the lower St. Lawrence Estuary, Canada. Mar. Ecol. Prog. Ser. 230: 211–224.

Plourde, S., P. Joly, J.A. Runge, J. Dodson and B. Zakardjian. 2003. Life cycle of *Calanus hyperboreus* in the lower St. Lawrence Estuary and its relationship to local environmental conditions. Mar. Ecol. Prog. Ser. 255: 219–233.

Pocklington, R. 1988. Organic matter in the Gulf of St. Lawrence. *In* Chemical oceanography in the Gulf of St. Lawrence. *Edited by P.M. Strain*. Can. Bull. Fish. Aquat. Sci. 220: 49–58.

Poulet, S.A., J.–P. Chanut et M. Morissette. 1986. Étude des spectres de taille des particules en suspension dans l'estuaire et le golfe du Saint–Laurent. I. Variations spatiales. Oceanol. Acta 9(2): 179–189.

Prouse, N.J., and D.V. Ellis. 1997. A baseline survey of dogwhelk (*Nucella lapillus*) imposex in eastern Canada (1995) and interpretation in terms of tributyltin (TBT) contamination. Environ. Technol. 18: 1255–1264.

Rabalais, N.N., R.E. Turner and W.J.Jr. Wiseman. 2000. Hypoxia in the Gulf of Mexico. J. Environ. Qual. 30: 320–329.

Ramade, F. 1979. Ecotoxicologie. Paris: Masson France, 2^{ième} éd.

Ray, S., B.P. Dunn, J.F. Payne, L. Fancey, R. Helbig and P. Béland. 1991. Aromatic DNA-carcinogen adducts in beluga whales from the Canadian Arctic and Gulf of St. Lawrence. Mar. Pollut. Bull. 22(8): 392-396.

Reeves, R., and E. Mitchell. 1984. Catch history and initial population of white whales (*Delphinapterus leucas*) in the River and Gulf of St. Lawrence, Eastern Canada. Naturaliste canadien 111: 63–121.

Rice, J., and D. Rivard. 2003. Proceedings of the zonal assessment meeting–Atlantic cod. DFO Can. Sci. Advis. Sec. Proceed. Ser. 2003/021, 151 p..

Richardson, W.J., K.J. Finley, G.W. Miller, R.A. Davis and W.R. Koski. 1995. Feeding, social and migration behaviour of bowhead whales, *Balaena mysticetus*, in Baffin Bay vs the Beaufort Sea–Regions with different amounts of human activity. Mar. Mamm. Sci. 11(1): 1–45.

Rignot, E., and P. Kanagaratnam. 2006. Changes in the velocity structure of the Greenland ice sheet. Science 311: 986–990.

Ringuette, M., M. Castonguay, J.A. Runge and F. Grégoire. 2002. Atlantic mackerel (*Scomber scombrus*) recruitment fluctuations in relation to copepod production and juvenile growth. Can. J. Fish. Aquat. Sci. 59: 646–656.

Rivkin, R.B., L. Legendre, D. Deibel, J.–E. Tremblay, B. Klein, K. Crocker, S. Roy, N. Silverberg, C. Lovejoy, F. Mesplé, N. Romero, M.R. Anderson, P. Matthews, C. Savenkoff, A.F. Vézina, J.–C. Therriault, J. Wesson, C. Bérubé and R.G. Ingram. 1996. Vertical flux of biogenic carbon in the ocean: is there food web control? Science 272: 1163–1166.

Robichaud, D., R.F.J. Bailey and R.W. Elner. 1989. Growth and distribution of snow crab, *Chionoecetes opilio*, in the southeastern Gulf of St. Lawrence. J. Shellfish Res. 8: 813–833.

Romare, P., and L.–A. Hansson. 2003. A behavioral cascade: Top–predator induced behavioral shifts in planktivorous fish and zooplankton. Limnol. Oceanogr. 48: 1956–1964.

Rosenberg, D.M., F. Berkes, R.A. Bodaly, R.E. Hecky, C.A. Kelly and J.W.M. Rudd. 2007. Large–scale impacts of hydroelectric development. Environ. Rev. 5: 27–54.

Rouleau, C., C. Gobeil and H. Tjälve. 2001. Cadmium accumulation in the snow crab. Mar. Ecol. Prog. Ser. 224: 207–217.

Roy, S., B. Sundby, A.F. Vézina and L. Legendre. 2000. A Canadian JGOFS process study in the Gulf of St. Lawrence. Deep–Sea Res. Part II 47: 377–384.

Royer, T.C., C.E. Grosch and L.A. Mysak. 2001. Interdecadal variability of Northeast Pacific coastal freshwater and its implications on biological productivity. Prog. Oceanogr. 49: 1–4.

Rulifson, R.A., and M.J. Dadswell. 1987. Mortality of fish passing through tidal, low–head hydropower turbines and possible mitigation strategies. Oceans 19: 944–949.

Runge, J.A., M. Castonguay, Y. de Lafontaine, M. Ringuette and J.L. Beaulieu. 1999. Covariation in climate, zooplankton biomass and mackerel recruitment in the southern Gulf of St. Lawrence. Fish. Oceanol. 8(2): 139–149.

Runge, J.A., and Y. Simard. 1990. Zooplankton of the St. Lawrence Estuary: the imprint of physical processes on its composition and distribution. *In* Oceanography of a large–scale estuarine system, the St. Lawrence. *Edited by M.I. El–Sabh and N.S. Silververg.* Coastal and Estuarine Studies 39. Springer-Verlag, Berlin. pp. 297–320.

Runge, J.A., and Y. de Lafontaine. 1996. Characterization of the pelagic ecosystem in surface waters of the northern Gulf of St. Lawrence in early summer: the larval redfish–Calanus–microplankton interaction. Fish. Oceanol. 5(1): 21–37.

Safe, S. 1984. Polychlorinated biphenyls (PCBs) and polybrominated biphenyls (PBBs): biochemistry, toxicology , and mechanism of action. Crit. Rev. Toxic. 13(4): 319–395.

Saint–Jean, S.D., S.C. Courtnay, E. Pelletier and R. Saint–Louis. 1999. Butyltin concentrations in sediments and blue mussels (*Mytilus edulis*) of the southern Gulf of St. Lawrence, Canada. Environ. Technol. 20: 181–189.

Saint–Louis, R., C. Gobeil and E. Pelletier. 1997. Tributyltin and its degradation products in the St. Lawrence Estuary (Canada). Environ. Technol. 18: 1209–1218.

Saint–Louis, R., S. de Mora, E. Pelletier, B. Doidge, D. Leclair, I. Mikaelian and D. Martineau. 2000. Hepatic butyltin concentrations in beluga whales (*Delphinapterus leucas*) from the St. Lawrence Estuary, and Northern Québec, Canada. Ap. Organ. Chem. 14: 218–226.

Sainte–Marie, B., and M. Lafrance. 2002. Growth and survival of recently settled snow crab *Chionoecetes opilio* in relation to intra– and intercohort competition and cannibalism: a laboratory study. Mar. Ecol. Prog. Ser. 244: 191–203.

Sainte–Marie, B., J.–M. Sévigny and M. Carpentier. 2002. Interannual variability of sperm reserves and fecundity of primiparous females of the snow crab (*Chionoecetes opilio*) in relation to sex ratio. Can. J.Fish. Aquat. Sci. 59: 1932–1940.

SARA (Species At Risk Act). Species list. [online] Available at http://www.sararegistry.gc.ca/species/default_e.cfm. [accessed 7 January 2005]

Saucier, F.–J., and J. Chassé. 2000. Tidal circulation and buoyancy effects in the St. Lawrence Estuary. Atmosphere–Ocean 38(4): 505–556.

Saucier, F.J., J. Chassé, M. Couture, R. Dorais, A. D'astous, D. Lefaivre and A. Gosselin. 1999. The making of a surface current atlas of the St. Lawrence Estuary, Canada. Proceedings of the 4th international conference on computer modelling of seas and coastal regions., pp. 87–97.

Saucier, F.–J., F. Roy, D. Gilbert, P. Pellerin and H. Ritchie. 2003. Modelling the formation of water masses and sea ice in the Gulf of St. Lawrence. J. Geophys. Res. 108(C8): 3269–3289.

Savaria, J.–Y., G. Cantin, L. Bosse, R. Bailey, L. Provencher et F. Proust. 2003. Compte rendu d'un atelier scientifique sur les mammifères marins, leurs habitats et leurs resources alimentaires. Rapp. manus. can. sci. halieut. aquat. 2647: v + 127 p.

Savenkoff, C., A.F. Vézina, T.T. Packard, N. Silverberg, J.–C. Therriault, W. Chen, C. Bérubé, A. Mucci, B. Klein, F. Mesplé, J.–E. Tremblay, L. Legendre, J. Wesson and R.G. Ingram. 1996. Distributions of oxygen, carbon, and respiratory activity in the deep layer of the Gulf of St. Lawrence and their implications for the carbon cycle. Can. J. Fish. Aquat. Sci. 53: 2451–2465.

Savenkoff, C., A.F. Vézina and Y. Gratton. 1997. Effect of a freshwater pulse on mesoscale circulation and phytoplankton distribution in the lower St. Lawrence Estuary. J. Mar. Res. 55: 353–381.

Savenkoff, C., A.F. Vézina, P. C. Smith and G. Han. 2001. Summer transports of nutrients in the Gulf of St. Lawrence estimated by inverse modelling. Estuar. Coast. Shelf Sci. 52: 565-587.

Savenkoff, C., A.F. Vézina, S. Roy, B. Klein, C. Lovejoy, J.–C. Therriault, L. Legendre, R. Rivkin, C. Bérubé, J.–E. Tremblay and N. Silverberg. 2000. Export of biogenic carbon and structure and dynamics of the pelagic food web in the Gulf of St. Lawrence. I. Seasonal variations. Deep–Sea Res. II 47: 585–607.

Savenkoff, C., H. Bourdages, M. Castonguay, L. Morissette, D. Chabot and M.O. Hammill. 2004. Input data and parameter estimates for ecosystem models of the northern Gulf of St. Lawrence (mid–1990s). Can. Tech. Rep. Fish. Aquat. Sci. 2531: vi+93 p.

Savenkoff, C., F. Grégoire, M. Castonguay, D.P. Swain, D. Chabot and J.M. Hanson. 2005. Main prey and predators of Atlantic mackerel (*Scomber scombrus L.*) in the northern and southern Gulf of St. Lawrence during the mid–1980s, mid–1990s, and early 2000s. Can. Tech. Rep. Fish. Aquat. Sci. 2619: v+29 p.

Savenkoff, C., L. Savard, B. Morin and D. Chabot. 2006. Main prey and predators of northern shrimp (*Pandalus borealis*) in the northern Gulf of St. Lawrence during the mid–1980s, mid–1990s, and early 2000s. Can. Tech. Rep. Fish. Aquat. Sci.: 2639: v+28 p.

Savenkoff, C., D.P. Swain, J.M. Hanson, M. Castonguay, M.O. Hammill, H. Bourdages, L. Morissette and D. Chabot. 2007a. Effects of fishing and predation in a heavily exploited ecosystem: comparing periods before and after the collapse of groundfish in the southern Gulf of St. Lawrence (Canada). Ecol. Model. 204 (1-2): 115-128.

Savenkoff, C., M. Castonguay, D. Chabot, M.O. Hammill, H. Bourdages and L. Morissette. 2007b. Changes in the northern Gulf of St. Lawrence ecosystem estimated by inverse modelling: Evidence of a fishery-induced regime shift? Estuar. Coast. Shelf Sci. 73 (3-4): 711-724.

Scheffer, M., S. Carpenter and B. de Young. 2005. Cascading effects of overfishing marine systems. Trends Ecol. Evol. 20(11): 579–581.

Scott, W.B., and M.G. Scott. 1988. Atlantic Fishes of Canada. Can. Bull. Fish. Aquat. Sci. 219: 731 p.

Sergeant, D.E. 1986. Present status of white whales *Delphinapterus leucas* in the St. Lawrence Estuary. Naturaliste canadien 113: 61–81.

Service hydrographique du Canada. 1997. Atlas des courants de marée: estuaire du Saint–Laurent, du Cap Bon–Désir à Trois Rivières. Pêches et Océans Canada. 108 p.

Sharp, G., R. Semple and B. Pilgrim. 2001. Distribution and abundance of marine plants in the nearshore of Cape Breton in potential oil and gas exploration areas. DFO Can. Sci. Advis. Sec. Res. Doc. 2001/117, 41 p.

Shih, C.–T., A.J.G. Figuera and E.H. Grainger. 1971. A synopsis of Canadian marine zooplankton. Bull. Fish. Res. Board Can. 177, 264 p.

Siah, A., J. Pellerin, J.–C. Amiard, É. Pelletier and L. Viglino. 2003. Delayed gametogenesis and progesterone levels in soft-shell clams (*Mya arenaria*) in relation to in situ contamination to organotins and heavy metals in the St. Lawrence River. Comp. Bioch. Physiol. Part C 135(2): 145-156.

Shugart, L. R., D. Martineau and P. Béland. 1990. Detection and quantitation of benzo(a)pyrene adducts in brain and liver tissues of beluga whales (*Delphinapterus leucas*) from the St. Lawrence and Mackenzie estuaries. Proceedings, International Forum for the future of the Beluga. *Edited by J. Prescott and M. Gauquelin*. Presses Université du Québec, Sillery, Québec, QC. pp. 219-223.

Silverberg, N., H.M. Edenborn and N. Belzile. 1985. Sediment response to seasonal variations in organic matter input. *In* Marine and estuarine geochemistry. *Edited by A.C. Sigleo and A. Hattori*. Lewis Publisher, Chelsea, Mi. pp. 69–79.

Simard, Y., and D. Lavoie. 1999. The rich krill aggregation of the Saguenay–St. Lawrence Marine Park: hydroacoustic and geostatistical biomass estimates, structure, variability, and significance for whales. Can. J. Fish. Aquat. Sci. 56: 1182–1197.

Simard, Y., D. Lavoie and F.J. Saucier. 2002. From plankton to whales: oceanography of a traditional whale feeding ground and marine park in the St. Lawrence estuary. Theme Session on Environmental Influences on Trophic Interactions. ICES CM 2002/N: 14.

Sirois, P., and J. Dodson. 2000. Influence of turbidity, food density and parasites on the ingestion and growth of larval rainbow smelt *Osmerus mordax* in an estuarine turbidity maximum. Mar. Ecol. Prog. Ser. 193: 167–179.

Sissenwine, M.P. 1984. Why do fish populations vary? *In* Exploitation of marine communities. *Edited by R.M. May*. Springer, New York. pp. 59–94.

Smith, B.S. 1981. Male characteristics in female mud snails caused by antifouling bottom paints. J. Appl. Toxicol. 1: 22–25.

Smith, T.G., and M.O. Hammill. 1986. Population estimates of white whales *Delphinapterus leucas*, in James Bay, Eastern Hudson Bay, and Ungava Bay. Can. J. Fish. Aquat. Sci. 43: 1982–1987.

Sorensen, E.M. 1991. Metal poisoning in fish. CRC Press, 374 p.

Squires, H.J., and E.G. Dawe. 2003. Stomach contents of snow crab (*Chionoecetes opilio*) (Decapoda, Brachyura) from the northeast Newfoundland shelf. J. Northwest Atl. Fish. Sci. 32: 27–38.

Starr, M., L. St–Amand and L. Bérard–Therriault. 2002. State of phytoplankton in the Estuary and Gulf of St. Lawrence during 2001. DFO Can. Sci. Advis. Sec. Res. Doc. 2002/067.

Starr, M., L. St–Amand, L. Devine et L. Bérard–Therriault. 2003. État du phytoplancton dans l'Estuaire et le Golfe du Saint–Laurent en 2002. DFO Can. Sci. Advis. Sec. Res. Doc. 2003/103.

Steven, D.M. 1974. Primary, and secondary production in the Gulf of St. Lawrence. Mar. Sci. Centre, M. Rep. 26 (McGill University).

St-Jean, S.D., S.C. Courtenay, É. Pelletier and R. St.Louis. 1999. Butyltin concentrations in sediments and blue mussels (*Mytilus edulis*) of the southern Gulf of St. Lawrence, Canada. Environ.Technol. 20: 181-190.

St-Jean, S.D., É. Pelletier and S.C. Courtenay. 2002a. Very low levels of water-borne butyltins modulate haemocyte function in the blue mussel, *Mytilus edulis*. Mar. Ecol. Prog. Ser. 236: 155-161.

St-Jean, S.D., É. Pelletier and S.C. Courtenay. 2002b. Haemocyte functions and bacterial clearance affected in vivo by TBT and DBT in blue mussels, *Mytilus edulis*. Mar. Ecol. Prog. Ser. 236: 163-178.

Strain, P. 1988. Chemical oceanography in the Gulf: present and future. *In* Chemical oceanography in the Gulf of St. Lawrence. *Edited by P.M. Strain*. Can. Bull. Fish. Aquat. Sci. 220: 159–173.

Sundby, B. 1974. Distribution and transport of suspended particulate matter in the Gulf of St. Lawrence. Can. J. Earth Sci. 11: 1517–1533.

Sutcliffe, W.H. Jr. 1973. Correlations between seasonal river discharge and local landings of American lobster (*Homarus americanus*) and Atlantic halibut (*Hippoglossus hippoglossus*) in the Gulf of St. Lawrence. J. Fish. Res. Board Can. 30: 856–859.

Syvitski, J.P.M., and E.W.H. Hutton. 1996. *In situ* characteristics of suspended particles as determined by the floc camera assembly FCA. J. Sea Res. 36(1/2): 131–142.

Templeman, W. 1985. Stomach contents of Atlantic wolffish (*Anarhichas lupus*) from the Northwest Atlantic. NAFO Sci. Counc. Stud. 8: 49–51.

Therriault, J.–C., and G. Lacroix. 1976. Nutrients, chlorophyll, and internal tides in the St. Lawrence estuary. J. Fish. Res. Board Can. 33: 2747–2757.

Therriault, J.–C., and M. Levasseur. 1985. Control of phytoplankton production in the lower St. Lawrence Estuary: Light and freshwater runoff. Naturaliste canadien 112: 77–96.

Therriault, J.–C., J. Painchaud and M. Levasseur. 1985. Factors affecting the occurrence of *Protogonyaulax tamarensis* and shellfish toxicity in the St. Lawrence Estuary: freshwater runoff and the stability of the water column. *In* Toxic Dinoflagellates. *Edited by D.M. Anderson, A.W. White and D.C. Baden*. Elsevier Science, New York. pp. 141–146.

Therriault, J.–C., L. Legendre and S. Demers. 1990. Oceanography and ecology of phytoplankton in the St. Lawrence Estuary. *In* Oceanography of a large–scale estuarine system, the St. Lawrence. *Edited by M.I. El–Sabh and N.S. Silververg*. Coastal and Estuarine Studies 39. Springer-Verlag, New York, Inc. pp. 269–290.

Therriault, J.–C, P.S. Galbraith, M. Starr and M. Harvey. 2002. Intrusions of Labrador Shelf waters into the Gulf of St. Lawrence and their potential influence on the plankton community and higher trophic levels. AZMP Bulletin PMZA 2: 12–15.

Tian, R.C., A.F. Vézina, M. Starr and F. Saucier. 2001. Seasonal dynamics of coastal ecosystems and export production at high latitudes: a modelling study. Limnol. Oceanogr. 46(8): 1845–1859.

Timme-Laragy, A.R., E.D. Levin and R.T. Di Giulio. 2006. Developmental and behavioral effects of embryonic exposure to the polybrominated diphenylether mixture DE-71 in the killifish. Chemosphere 62:1097.

Trites, R.W. 1972. The Gulf of St. Lawrence from a pollution point of view. *In* Marine Pollution and Sea Life. *Edited by G. Ruivo.* FAO, Fishing News Books, London, UK. pp. 59–72.

Verbeek, N.H., and T.M. McGee. 1995. Characteristics of high-resolution marine reflection profiling sources. J. Appl. Geophys. 33(4): 251–269.

Vézina, A.F., C. Savenkoff, S. Roy, B. Klein, R. Rivkin, J.–C. Therriault and L. Legendre. 2000. Export of biogenic carbon and structure and dynamics of the pelagic food web in the Gulf of St. Lawrence Part 2. Inverse analysis. Deep–Sea Res. Part II 47: 609–635.

Viglino, L., É. Pelletier and L.E.J. Lee. 2006. Butyltin species in benthic and pelagic organisms of the Saguenay fjord (Canada) and imposex occurrence in common whelk (*Buccinum undatum*). Arch. Environ. Contam. Toxicol. 50: 45-59.

Vincent, B. 1990. The macrobenthic fauna of the St. Lawrence Estuary. *In* Oceanography of a large–scale estuarine system, the St. Lawrence. *Edited by M.I. El–Sabh and N.S. Silververg.* Coastal and Estuarine Studies 39. Springer-Verlag, Berlin. pp. 321-343.

Vladykov, V.D. 1944. Étude sur les mammifères aquatiques. III. Chasse, biologie, et valeur économique du marsouin blanc ou béluga (*Delphinapterus leucas*) du fleuve et du Golfe Saint–Laurent. Département des Pêcheries, Québec. 194 p.

Vörösmarty, C.J., M. Meybeck, B. Fekete, K. Sharma, P. Green and J.P.M. Syvitski. 2003. Anthropogenic sediment retention: major global impact from registered river impoundments. Global Planet. Change 39: 169–190.

Walker, M.K., and R.E. Peterson. 1991. Potencies of polychlorinated dibenzo-p-dioxin, dibenzofuran, and biphenyl congeners, relative to 2,3,7,8-tetrachlorodibenzo-p-dioxin, for producing early life stage mortality in rainbow trout (*Oncorhynchus mykiss*). Aquat. Toxicol. 21: 219-238.

Waring, C.P., and A. Moore. 2004. The effect of atrazine on Atlantic salmon (*Salmo salar*) smolts in fresh water and after sea water transfer. Aquat. Toxicol. 66: 93-104.

Weise, A., M. Levasseur, F.J. Saucier, S. Senneville, E. Bonneau, S. Roy, G. Sauvé, S. Michaud and J. Fauchot. 2002. The link between precipitation, river runoff, and blooms of the toxic dinoflagellate *Alexandrium tamarense* in the St. Lawrence. Can. J. Fish. Aquat. Sci. 59: 464–473.

Wirgin, I, C. Grunwald, S. Courtenay, G.–L. Kreamer, W.L. Reichert and J.E. Stein. 1994. A biomarker approach to assessing xenobiotic exposure in Atlantic tomcod from the North American Atlantic coast. Environ. Health Persp. 102: 764–770.

Wolffish Recovery Team. 2003. National recovery plan for the northern wolffish, *Anarhichas denticulatus*, and spotted wolffish, *Anarhichas minor*, in eastern Canadian waters. National Recovery Plan. Recovery of Nationally Endangered Wildlife (RENEW). Ottawa, Ontario. (Draft document, February, 2004).

Worm, B., and R.A. Myers. 2003. Meta–analysis of cod–shrimp interactions reveals top–down control in oceanic food webs. Ecology 84(1): 162–173.

Yeats, P.A. 1988a. Distribution and transport of suspended particulate matter. *In* Chemical oceanography in the Gulf of St. Lawrence. *Edited by P.M. Strain*. Can. Bull. Fish. Aquat. Sci. 220: 15–28.

Yeats, P.A., 1988b. Nutrients. *In* Chemical oceanography in the Gulf of St. Lawrence. *Edited by P.M. Strain*. Can. Bull. Fish. Aquat. Sci. 220: 29–48.

Yeats, P.A., B. Sundby and J.M. Bewers. 1979. Mangenese recycling in coastal waters. Mar. Chem. 8: 43–55.

Zakarauskas, P., D. Chapman and P. Staal. 1990. Underwater acoustic noise levels on the eastern Canadian continental shelf. J. Acoust. Soc. Am. 53: 2064–2071.

Zakardjian, B.A., Y. Gratton and A.F. Vézina. 2000. Late spring phytoplankton bloom in the lower St. Lawrence Estuary: the flushing hypothesis revisited. Mar. Ecol. Prog. Ser. 192: 31–48.

Zakardjian, B.A., J. Sheng, J.A. Runge, I.A. McLaren, S. Plourde, K.R. Thompson, and Y. Gratton. 2003. Effect of temperature and circulation on the population dynamics of *Calanus finmarchicus* in the Gulf of St. Lawrence and Scotian Shelf: study with coupled, three–dimensional hydrodynamic, stage–based life history model. J. Geophys. Res. 108(C11), 8016, doi: 10.1029/2002JC001410, 2003.

Zwally, H.J., M.B. Giovinetto, J. Li, H.G. Cornejo, M.A. Beckley, A.C. Brenner, J.L. Saba and D. Yi. 2005. Mass changes of the Greenland and Antarctic ice sheets and shelves and contributions to sea–level rise: 1992–2002. J. Glaciol. 51: 509–527.